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APPLIED GEOPHYSICAL METHODS IN AMERICA.*

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INTRODUCTION.

THE methods of applied geophysics in practical use in economic geology are largely foreign born. The redeeming feature to an American is the way that they have been taken up by the American oil companies. The methods in considerable practical use are four: The Eötvös gravimetric, the seismic, the electric and the magnetic. The Eötvös gravimetric method was developed by Baron Eötvös of Hungary during the latter part of the past century. The seismic (or sonic) method was worked out by Fessenden of the United States in 1913, but its present development is due largely to a later but independent development of the method by Mintrop of Germany. The application of electric methods to prospecting has been the subject of experimentation for nearly a century; the recent successful development of practical instruments and technique for commercial application of the methods was by Lundberg and Nathorst in Sweden, Schlumberger in France, Gella in Austria, and Sundberg in Sweden. The magnetic method has been in practical use for over a half century in connection with the magnetic iron ores. The present application of the method to faintly magnetic ores and to geologic structural mapping dates from the recent invention by Schmidt of Germany of his adaptation of the Lloyd balance and from Schuh's mapping of the Lübteen salt dome, Germany, with the Schmidt Lloyd

* Data from papers by Ambrown, Heiland, Haanel, Sundberg, Schlumberger, Krahman and from original sources.

balance. These methods have been rapidly taken up by the oil companies. The recognition of the methods by schools and surveys has been much greater in Europe than in America. The record of these methods in prospecting in the Gulf Coast has been brilliant. The methods show interesting potentialities for research in pure science problems in geology. The present geologic status of the methods is that the instruments and technique of observation has been developed much farther than the general knowledge of the geologic interpretation of the results. Research on and with the methods is being done almost solely by commercial companies, by whom the results of the research mostly will not be released. These methods offer an interesting and almost untouched field of research to schools both of pure and of applied science.

A review by an American of America's part in the inception of those new geophysical methods, which have been hailed by DeGolyer as probably marking the beginning of a new era in the science of economic geology, must be made with humility. America likes to think of herself as foremost in invention and engineering—not excepting mining engineering and oil geology. American scientists in the past have considered the application of some such methods as are now being applied, but except in the case of the magnetic methods in prospecting for highly magnetic ores, the attempts to develop them were unsuccessful. The new methods in actual practice very largely are foreign born; the instruments were invented or adapted, and the technique of their successful application to practical geologic problems was worked out by foreign scientists in foreign lands. The impetus to the use of the methods in America, furthermore, has come in general from the methods seeking America, rather than America seeking the methods. The redeeming feature to an American is the way in which the methods have been received by certain of the American oil companies, the brilliant success that the oil companies have had in applying the methods in the Gulf Coast, the progress that the oil company geophysicists have made in a very short time in developing the technique of the methods and, in the case of

the seismic (or sonic) methods, in the perfection of radically improved instruments, and the brilliant possibilities that these methods afford the American geologist of looking down, as it were, for several miles into the earth's crust.

The geophysical methods actually in considerable practical use are: The Eötvös gravimetric method, the seismic or sonic method, the electric methods, and the magnetometric methods; other methods have possibilities, but in their present state of development have not been demonstrated to be of practical importance.

THE METHODS.

Gravimetric Method.—The Eötvös torsion balance gravimetric method was conceived and perfected by Baron Eötvös in Hungary during the late '80's and the '90's of the past century. The applicability of the method for regional geologic surveys had been well shown by 1906 by his work in Hungary. Its applicability to the surveying of local structures, such as salt domes, was shown by Böckh of Budapest in 1917. The results of the work in Hungary were well reported in some ten papers in German, French, Hungarian and International Journals from 1890 to 1918. The method was used by the Germans during the World War. It was taken up by the Anglo-Persian Oil Company and by the Royal Dutch Shell Oil Company at the end of the War. Its first introduction into this country and into Mexico was due simultaneously to DeGolyer of the Rycade-Amerada oil companies and to the Royal Dutch Shell. A very considerable part of the impetus of the present growing use of the method is due to the advertisement and demonstration of it by the German and the Hungarian manufacturers of the balance and by a German consulting geophysical company, which entered this country on its own initiative. Until recently most of the observers operating torsion balances in this country had been trained either at Berlin or at Budapest. The only vital improvement of the Eötvös balance has been by Schweydar of Berlin. One foreign oil company probably operates at least fifty per cent. more Eötvös torsion balances than all the American oil companies put together.

Seismic Method.—The application of the seismic (or sonic) method to the determination of local geologic structure was first worked out in 1913 by Fessenden, who in a series of field experiments near Framingham, Mass., developed the instruments and technique to the point where he was able to make practical application of the method. He tried to interest some mining companies in the method, but being unsuccessful, he dropped work with the seismic (or sonic) method for other lines of invention, and no practical application of his results seems to have been made. Eckhart, Haseman, Karcher, and McCollom in 1921 experimented in Oklahoma with a seismic method. Their results at the time seemed rather negative but very recent work shows that the apparent failure at that time was due largely to lack of encouragement and to limited financial resources. The initial impetus to the present extensive use of the seismic (or sonic) method is due very largely to L. Mentrop, and his "Seismos" Company of Hannover, Germany. Working as a junior colleague of Wiechert of Göttingen, he developed his instruments and technique during the war, and by 1921 had demonstrated the potentiality of the method, but apparently had not done much actual surveying of geologic structure. Late in 1923 his method was introduced into Mexico by the Royal Dutch Shell, and about the same time he got the Marland Oil Company to try out his method in the Mid-Continent area, and slightly later, the Gulf Production Company to try out the method on the Gulf Coast salt domes. The success of the method in the Gulf Coast is due in very considerable part to the encouragement and support given to it from the start by L. P. Garret of the Gulf Production Company, who previously had imaginatively foreseen the possibilities of the method in reconnaissance for new salt domes. The discovery by the seismograph of several salt domes late in 1924 gave great impetus to the use of the method. By the spring of 1926, Ricker, Eckhart, McCollom, Rieber and Karcher, all Americans, had perfected seismographs, some of them radically different from Mintrop's seismograph, and had radically improved some of the instrumental technique of the method, and during the year

several additional seismographs of American design were tried out in the field. The best American method is probably somewhat superior to Mintrop's. Up to 1926, the "refraction" method was the only one in practical use, although there had been some experimentation in attempt to perfect a method of using waves directly reflected back at a high angle. During 1926, the Geophysical Research Corporation perfected the instruments and technique of a reflection method to the point of practical applicability.

Electrical Methods.—The application of electrical methods to prospecting for ores has been the subject of experimentation for nearly a century. Fox did some notable work in 1830 at Cornwall, England, and somewhat later Reich and Erhard at Freiburg in Germany, and in 1880 Barus at Eureka and Comstock Lode, Nevada. In 1914, Wells in America made a notable study of electric activity in ore deposits. About 1900 in America, a "resistance" method of prospecting was devised by Broun, and slightly later was improved upon by MacClatchey. About 1902, in America, Daft and Williams devised a method in which an electric current was sent through the earth and the field of force set up was listened in on with a telephone. In Sweden, the Daft and Williams method was tried out by Peterson and Wallin in 1906 and served as the starting point for a decade of Swedish experimentation on electrical prospecting, but no practical apparatus or method was worked out until Lundberg and Nathorst invented theirs in 1918. The value of their method in prospecting for non-magnetic ores was demonstrated by the discovery by it of the Kristineburg (pyrite) orefield in 1918–1919 and of the Bjurfors (Fe, Zn, Cu sulphide) orefield in 1922. In France, beginning in 1912, Schlumberger worked out another "equipotential" electric method. Later an "induced current" method was worked out by Sundberg in Sweden and a method tracing the orientation of the equipotential lines was worked out by Gella, an Austrian engineer, with German support in the later stages of experimentation. As the electrical methods were introduced primarily for prospecting for ore deposits, and are only

just beginning to be tried out in oil geology, the writer is not familiar with the details of the introduction of the methods, but understands that the impetus which the electrical methods of prospecting have in this country is due largely to American branches of Swedish, French, and German consulting prospecting companies. Several mining and oil companies are carrying on experimentation with electrical methods.

Magnetometric Methods.—The magnetometric methods are the oldest of the geophysical methods in point of practical application in economic geology. The date of their first use, referred to in the literature, is given by Heiland as 1760, in New Jersey. In 1843, impressed with Lamont's work with his newly invented (magnetic) theodolite, von Wrede recognized the potentiality of magnetometric methods in prospecting for magnetic ores. The method was not put on a firm foundation until the publication of Thalen's paper in Sweden in 1879, and was improved in 1899 by Smyth (of United States) and Uhlich (of Germany), in 1910 by Gyllenskoeld (of Sweden), in 1924 by Griesser (of Germany), in 1926 by Haalek (of Germany). Practical use of the method in connection with magnetic ores in Sweden dates from the 1860's; in America similar surveys were made among others by Brooks in 1873, Smock in 1875, Smyth in 1899, Hotchkiss in 1915, and others.

The connection of magnetic anomalies with regional structure was shown by Locke in 1846 in United States; by Kreil in 1849 for the Alps; by Naumann in 1887 in Japan; by Caspari in Madagascar; by Ruecker and Thorpe in 1890 in Great Britain; by Palezzo in 1892 in Italy; by Eschenhagen in 1898 in Germany; by Schueck in 1898–1902 in Germany; and by Farr in 1918 in New Zealand.

The connection of magnetic anomalies with more local structures was shown by Ruecker in 1890 in England; by Moureaux in 1904–07 in France; by Pfaff's (of Germany) interpretation in 1913 of the earlier work of Lamont, Merserschmidt and others in Bavaria; by Deecke in 1906 in Germany; by Ricco in 1908; by Tornquist in 1911 in Germany; by Eötvös in 1900–1912 in

Hungary; by Goellnitz in 1908–1910 and 1919 in Saxony; and by Cox in 1918 in England. In United States in 1909, Becker stated his belief in the possibility of prospecting for geologic structures and oil by magnetic methods.

As the older instruments did not combine high sensitivity, easy portability, and high speed of observation, the mapping of weak magnetic effects due to very weakly magnetic ores and to relatively non-magnetic masses, such as salt domes, did not become practical in economic work until A. Schmidt's invention (in Germany) in 1914 of a very sensitive but practical field balance as an adaptation of the old Lloyd magnetic balance. Other magnetic balances and other types of magnetic instruments, some of them American, are now available. The present impetus to the use of the magnetic methods in economic geology started from Schuh's mapping of the Lubtheen salt dome in Germany in 1919, and was accelerated by the work of other German geologists likewise using the Schmidt-Lloyd balance, and by the general interest in the application of geophysical methods to the problems of economic geology. The Schmidt-Lloyd balance was first brought into this country by the Rycade-Amerada Companies, but the present use of magnetic methods is due largely to the advertisement of them by the German instrument company making the Schmidt-Lloyd balance.

PRESENT DAY USE OF THE METHODS.

Now that these methods have been brought to this country, they are being taken up rapidly by the oil companies and to some extent by the mining companies. Table I gives an approximate census of the geophysical instruments in use by American oil companies or in economic work in United States.

Many of the oil companies in Texas, Louisiana, and Oklahoma that are not now using the geophysical methods apparently are considering the advisability of trying them, and as soon as the oil situation improves there will probably be a rush by these companies to initiate such work.

TABLE I.

GEOPHYSICAL INSTRUMENTS IN USE BY AMERICAN OIL AND MINING COMPANIES.

	Seismograph[1] Troops.			Torsion Balances.			Magneto-meters.		Electric Method.
	G. R. C.	Seismos.	Other.	Suss.	B'berg.	Other.	Vert.	Other.	
Amerada Pet. Corp.	3	—	—	4	—	—	3	1	—
Atlantic O. P. Co.	—	—	*[2]	4	—	—	3	—	—
Dixie Oil Co.	1	—	—	1	1	—	—	—	—
Geophysical Research Corp.	*	—	—	—	—	*	—	—	*
Gulf Prod. Co.	2	1	—	—	14	—	15	4*	*
Marland O. Co.	—	—	*	—	1	—	5	1	?
Midwest O. Co.	—	—	—	—	2	—	2	—	—
Orange P. Co.	—	—	—	1	—	—	—	—	—
Phillips Pet. Co.	—	—	*	—	—	—	4	—	—
Pure Oil Co.	2	—	—	2	—	—	(7)	—	—
Roxana Pet. Co.	1	2	1	—	30	—	6	—	*
Shell Co. of Cal.	—	?	—	—	?	—	—	—	?
T. Texas Co.	—	—	—	2	—	—	4	—	—
Carter O. Co.	—	—	—	2	—	—	?	—	—
Consulting Companies	—	—	*	14	4	1	—	3	?
Miscellaneous	—	1	10*	4	—	6*	6	2	?
Ordered but not delivered	2	—	—	—	?	—	25		

[1] A seismograph troop consists normally of three or four receiving units, each with one seismograph, and of one firing unit.

[2] * = small seismograph troops; experimental troops, instruments, or methods; obsolete or impracticable instruments.

The total expenditures of the oil companies in operating geophysical parties and instruments in Texas, Louisiana, Oklahoma, New Mexico, and Mississippi have been and apparently are large. The Gulf Company already has spent more than three million dollars and at present apparently is spending about $65,000 per month. The Roxana Petroleum Co. is apparently spending about $90,000 per month. Several other companies are spending about $20,000 per month. The total expenditure in those states probably amounts to some $400,000 per month. Those figures do not include the cost of leasing or drilling but merely the operation of the geophysical work.

The geophysical work for the most part was done by foreign consulting geophysical companies or by foreign trained observers until recently. Most of the companies are now attempting to put

in their own geophysical departments, except in the case of the seismic (or sonic) method, where practically all of the work is being done by the German "Seismos" Company or the American "Geophysical Research Corp." A few companies employ competent geophysicists and are engaged in research work on the geophysical methods, as for example the Amerada Petroleum Corp.-Rycade Oil Corp. through their common subsidiary, the Geophysical Research Corp.; the Humble Oil and Ref. Co.; the Marland Oil Co.; and the Atlantic Oil Prod. Co.

Mining companies are now utilizing geophysical methods to a considerable extent but their work is only a small fraction of what is being done by the oil companies. There has been considerable use of the different electrical methods, especially in Canada and the Western States, with varying degrees of success. The torsion balance is being tried out in the Michigan iron ore district, according to unconfirmed report, with considerable success. The torsion balance and the magnetometer have been tried out in the Missouri lead and zinc districts with indifferent success.

In spite of the extensive use of these geophysical methods by the American oil companies, the methods are being used to even greater extent by foreign oil companies. The Royal Dutch Shell inclusive of its American subsidiaries is doing as much work probably as all the American oil companies (exclusive of the Royal Dutch Shell American subsidiaries) put together. Two years ago the Royal Dutch Shell was operating 60 torsion balances and several Seismos troops in various parts of the world. The Anglo-Persian Oil Co. also is a very extensive user of geophysical methods.

The general recognition of the applied geophysical methods by the schools and government institutions has been very much greater in Europe than in America. The Russian mining code recognizes and provides for the use of geophysical methods of exploration—several counties in southeastern Texas and southern Louisiana recognize them by ordinance or court injunction, but the animus of the recognition is that certain influential large land owners wish to force the geophysicist off the roads so that the oil

companies will have to lease their lands before prospecting them. The Institute of Practical Geophysics of the Supreme Council of Public Economy at Leningrad is perhaps the only government institution solely devoted to the economic application of geophysical methods in mining and geology, and next to the German *Zeitschrift für Geophysik*, its bulletin has to its credit in 1925 and 1926 the most papers on the theory and application of those methods. The Russian "Institute for Applied Mineralogy and Petrography, Lithogea" at Moscow is listed by the Geologen Kalendar as having a section for prospecting for ore by geophysical methods. The Prussian Geological Survey has established a section for applied geophysics. The Swedish Geological Survey has been interested in the development of the electric and magnetic methods. The Geological Survey of Great Britain a year ago was seriously considering the use of the methods. Two members of the staff of the Science Museum of London are doing considerable work in applied geophysics, especially in the application of the torsion balance, and have most of the important articles in English on the torsion balance to their credit. Although the data are now somewhat out of date, the distribution of the professorships of geophysics of the world as listed by the Geologen Kalendar for 1925–26 is significant of America's rather slight recognition of geophysics in the past; Russia 8 (and 1 instructorship), divided among three institutions, Germany 8 (and 2 instructorships) divided among 8 institutions, France and Spain 2 each, Czechoslovakia and Italy 1 each, and Lithuania 1 instructorship. There are also several professors in Germany, Austria, and Hungary who are known to the writer to be giving much attention to the new methods of applied geophysics. The University of Göttingen is reported to have undertaken a large program of applied geophysical study and it was under Wiechert of the Seismological Observatory at Göttingen that Mintrop developed his seismic (or sonic) method. Many of the professorships of geophysics listed in the Geologen Kalendar are primarily for the older or "pure" geophysics, especially seismology, but several of the professors themselves are now interested in the new practical applications.

In the older or " pure " geophysics, America has had and still has an honorable place, through the work of the Geophysical Laboratory, the Bureau of Terrestrial Magnetism, the Bureau of Standards, and the U. S. Coast and Geodetic Survey. But to the modern methods of applied geophysics, America as yet has contributed no important paper giving original data. At the present time, however, there is shown an awakened interest by others than the commercial companies; the Colorado School of Mines has started a department of geophysics with as ambitious a program as any of the foreign schools, although the chair of geophysics is held by a young German geophysicist. Several other American schools are considering seriously the establishment of professorships or instructorships of geophysics. The U. S. Bureau of Mines is starting an investigation of the various geophysical methods of prospecting, and during the past summer coöperated with Prof. Heiland of the Colorado School of Mines in a field study of the application of the torsion balance to certain mining problems.

RESULTS IN THE UNITED STATES.

The record of geophysical methods in prospecting in the salt dome area of Texas and Louisiana has been brilliant. In the 15 years preceding the introduction of the geophysical methods into the area of the coastal group of domes, some six new salt domes had been discovered and geologists had almost given up the attempt to find new domes by surface indications. Since the introduction into that area some four years ago, of the torsion balance and seismograph, there have been discovered some twenty-three new salt domes; four of them are at localities at which there were indications suggestive, but not strongly indicative, of the presence of a salt dome. Ten of the domes have been proved by drilling. The other thirteen have not been drilled. In the east Texas salt dome area, seismograph troops started hurriedly in the Spring, and in the first two months discovered six salt domes or structures, none of which have been drilled as yet. Although doubt is expressed by some of the reliability of the seismograph to indicate the presence of deeply buried salt domes (below 3,500

feet—1,100 meters), the indication of the shallower domes is considered by the Gulf Coast operators sufficiently reliable so that leases and royalties command the same prices as if a well had been drilled into the salt. The torsion balance method has shown the capacity in some cases, but not always, of delimiting the dome and the contours of the top of the cap with an accuracy of 5–10 per cent. By geophysical methods, a previously unsuspected salt dome in the Gulf Coast can be discovered, delimited and, in domes with a moderately massive cap rising above two thousand feet (600 meters), the top of the cap can be contoured with a fair, and in some cases a high, degree of accuracy, entirely in advance of drilling.

The ultimate value commercially of the salt domes discovered by the torsion balance and seismograph can not be evaluated yet, as the prospecting of many known salt domes has proved to be long and tedious, but the results to date are as follows: apparently one first class or very good second class oilfield (Starks), one oilfield that will be second class or better (Fausse Pointe), three oilfields at least of the third class (Nash, Orchard and Allen), and one first class sulphur field (Long Point). The total oil reserves of these fields conservatively stated, are not less than 40 million barrels and well may be more than 100 million barrels recoverable by present methods of production. The sulphur reserves of the Long Point dome, at a guess, are between 5 and 10 million tons. The sulphur rights at Long Point have been sold recently for a sum that is reported to be more than a million dollars in cash, the same amount out of sulphur, a fifty per cent. interest in the net profits, and a dollar a ton royalty.

A much more difficult task is faced by the geophysical methods elsewhere than on salt domes, for few geologic structural situations present such clean cut and exaggerated structure with such differences in physical properties as do the Gulf Coast salt domes composed as they are of a homogeneous plug of rock salt and cap of massive anhydrite and limestone intruded from thousands of feet into unconsolidated Tertiary sands and clays. To work the other areas, a new technique of operation and interpretation has

to be perfected—in very considerable part on the basis of experience—and is in the process of being perfected.

The seismic (or sonic) method has been demonstrated to elucidate the more complicated situation prevailing in the East Texas salt dome area, and in places at least, to yield information regarding faults along the Luling-Powell fault line zone and in northern Louisiana, and from its work elsewhere there would seem to be no doubt that by means of the seismograph the top of the first massive salt, limestone or anhydrite bed, in the West Texas Permian basin can be mapped.

The torsion balance is being tried out extensively in the Mid-Continent and West Texas areas, but as yet little drilling has been done on structures discovered by it. In the Seminole district, the Bowlegs oilfield was predicted in advance from torsion balance work and the eastward and north-northwestward extension of Earlsboro. In Cooke Co., the torsion balance outlined in advance the large buried Ordovician-Pre-Cambrian ridge extending from the Bulcher oilfield south-southeastward past Era into Denton Co., and indicated in advance that the Bulcher oilfield lay just below the crest on the northeast flank. In southern Oklahoma, the torsion balance very clearly would have led to the discovery of the Healdton, Hewitt, and Robberson oilfields had they not already been discovered and also would have led to the discovery of some of the lesser oilfields. The torsion balance also has given interesting results in the Texas Panhandle.

The magnetometer has been shown to give interesting and valuable results in the Texas Panhandle and along the similar Hambro-Nocona-Bulcher-Era Ordovician-Pre-Cambrian buried ridge, but elsewhere seems to be unreliable in its indication of oil structures.

Although the various electric methods have been and are being tried out on the oil structures, they have apparently scored no successes and the Gella method is reported to have scored two clean cut failures, and the results of a long and extensive series of tests with the Schlumberger method on oil structures are apparently unfavorable. Failures of the geophysical methods at

present may indicate, however, merely inadequate development of the technique of operation of the method or of interpretation of the results. The electric methods are reported to have had better success in prospecting for metallic mineral deposits.

POSSIBILITIES.

The place of these new, "applied" geophysical methods is in no way restricted to economic geology. Most of the methods show interesting potentialities for important pure science research. Although Wiechert and others have constructed semi-portable seismographs, there are a considerable series of seismologic problems whose solution has awaited a really portable seismograph; the more portable of the instruments used in the Gulf Coast, such as a G. R. C.-Karcher type seismograph, has the same portability as the light automobile on which it is mounted and the station can be set up in twenty minutes and can be dismounted, and packed ready to move in ten minutes. As the receiver of the G. R. C.-Karcher type seismograph is automatic, needs no attention, and is connected with the amplifying and recording apparatus by a cable, as many receivers could be set out in as many directions and at such distances from an observatory as desired and as practicable to string out the cable. An observatory with a receiver at each apex of an equilateral triangle three to nine miles on a side should be able to do some interesting new work on earthquakes.

The torsion balance has interesting possibilities. There is a very good possibility that it could give the petrologist interesting new data regarding the form, composition and depth of such igneous bodies as batholiths, volcanic plugs, and laccoliths. The glacial geologist could use it to map pre-glacial channels buried under fluvio-glacial deposits. The structural geologist could use it to map buried mountain ranges and the conformation of the surface of the basement in many sedimentary basins. The geodesists interested in isostasy could use the torsion balance to advantage to determine the size and approximate oder of depth of many of the gravity anomalies observed at the pendulum stations. With the field magnetometers, which are the simplest, the least costly, and the least expensive to operate of the field geophysical

instruments in use in economic geology, extensive areal surveys could be made of the variation of terrestrial magnetism, the anomalies in which should give clues to anomalies of geologic structure in the subsurface. With these new geophysical methods in geology, however, as with any newly discovered scientific tool, it is difficult to predict just what their usefulness and contribution to geology will be, but they give a means of observing certain physical properties, *i.e.*, mass, conductivity of seismic waves, magnetic conductivity, electric conductivity, of rock masses which cannot be observed by ordinary physical methods of sight and touch, and they afford, therefore, a certain amount of insight into the make-up of a region that at present is penetrated sparingly by drill and shaft and only to a shallow depth.

The present geological status of these applied geophysical methods might be compared crudely to the situation that would arise if an oil company sent out an engineer with an elementary knowledge of geology to detail an area with a single conspicuous key bed. He would be able to bring in a fairly accurate structure-contour map of the surficial structure and if the structure happened to be simple, his naive interpretation of the structure of the oil bearing horizons might prove to be correct. But if an unconformity or two lay between the surface and the oil bearing horizons, his interpretation of the structure of the latter would be wild. In the case of the applied geophysical methods, the physicist has gone much farther in the perfection of the instruments and of the technique of making the surveys than the geologist has in the interpretation of the results of those surveys. As the instruments in use are on the whole rather simple to operate and as the operations and calculations have been reduced to a rule of thumb procedure, it does not take long to train an observer who can make an accurate map of the variation of gravity, or magnetism, over a given area; the difficulty comes in the interpretation of the geologic structure from the results of the geophysical surveys. As the result of four years experience with torsion balance surveys in nearly all parts of Texas and Oklahoma and in parts of Kansas and Louisiana, and as the result of over a year's work by a professor of

mathematics on the mathematics of interpretation the writer is more and more impressed with the intricacies of interpretation of the results and with the necessity of a common sense background of experience with a geophysical method for interpretation of its results and, not least, for an evaluation of the limitations of the methods. A great danger at the present time to the full realization of the potentialities of those methods lies in the tendency that a company trying out a method will start out with one or two instruments, allow them to work a few months on known structures, and then attempt to realize on the method. On account of the lack of experience in interpretation, the chances are that the first tests made as the result of that geophysical survey will be failures. And although executives who have had much experience with geology do not expect fifty per cent. of successes in tests drilled on geology, they will condemn a geophysical method on the result of a few failures. The situation with those methods also is the same as with all tools of the economic geologists, that each works brilliantly under some geologic conditions, is of some use in others, and is useless in yet others, and it is very largely by experience that those conditions can be learned.

Practically, but not quite, all the research on and with the applied geophysical methods is being carried on in this country by the geophysical departments of a very few oil companies, by a very few consulting geophysical companies and by two or three mining companies. As the result of that work, the instruments, methods, and technique will be developed along lines that promise to be of immediate commercial advantage. Some "pure" research on geologic problems necessarily is done concomitantly with work on the economic problems and once in a while economic geophysicists manage to get a chance to do a piece of research that is only vaguely of economic importance, but improved technique of operation of the methods and of the interpretation of the results of the geophysical surveys will be kept by each company as much its own secret as possible. Considerable vague general information will leak out about the economic results but little accurate detailed information about the geologic results of geo-

physical surveys will find its way into the literature. As the geophysical methods are proving themselves a powerful tool in economic geology, any American mining school which pretends to give a thorough course in geologic prospecting must recognize them, and any American mining school which wishes to do research will find an inviting and almost virgin field in the codification, supplementation, and publication of accurate information in regard to present knowledge of applied geophysical methods and in their extension and perfection in the lines not covered by present economic research. American university geologic departments will find in the application of those methods to problems of geology a nearly virgin field of research that promises interesting possibilities.

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The following bibliography lists the more important papers in English on the applied geophysical methods. If there is no satisfactory paper in English, reference to a foreign paper is given. The literature in German is much more extensive than that in English and comprises most of the papers giving original data. The most complete descriptions of all the methods in one work are to be found in the textbooks by Ambronn and Gutenberg. If a detailed comprehensive view of the modern methods of applied geophysics in geology is desired, those textbooks and the various original papers listed by Heiland should be consulted.

General

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MAGNETIC, ELECTROCHEMICAL AND PHOTOCHEMICAL TESTS IN THE IDENTIFICATION OF OPAQUE MINERALS.

H. E. McKINSTRY.

INTRODUCTION.

With the growing importance of the microscope as a means of studying the paragenesis of metallic ores, the problem of identifying the minerals which are observed in polished sections is yielding to attack from a number of angles. Where the minerals occur in minute grains their determination is particularly difficult and certain special methods are often of great aid. A few of these have been made use of by the writer. Although not altogether new, they were applied in a manner having some aspects of novelty and for this reason they may be of interest to other workers.

A method of testing the magnetic properties of small grains, a method of observing the behavior of minerals between electrodes in a reagent, and the results of strong illumination on the silver minerals will be described in this paper.

The writer is indebted to Professor L. C. Graton for many ingenious suggestions during the course of the work, as well as for his inspiring enthusiasm.

TESTING FOR MAGNETISM.

An attempt was made to construct a magnetized needle, delicately suspended, that could be seen under the microscope and made to respond to the attraction of magnetic grains in the section. In order to make a more concentrated magnetic field and limit the influence as far as possible to a single grain, the straight needle was discarded and a delicate horseshoe magnet substituted.

This was made by breaking off the top half of the eye of a fine steel sewing needle and magnetizing it.

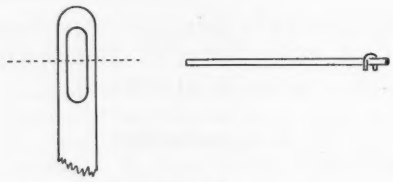

FIG. 1. Magnet made from the eye of a needle, mounted on horsehair with sealing wax.

One problem was to find a fiber of the proper rigidity on which to mount the horseshoe. Glass fiber was tried but its fragility was exasperating. Wires of aluminum and copper were used temporarily but their weight caused them to vibrate unduly. Finally a horsehair was selected as the most satisfactory support. A piece about 10 cm. long was attached to a glass tube by means of sealing wax and on the other end of the hair was fixed the magnet, straddling the hair and also fastened with wax. Thus the horsehair, supported at one end and carrying the magnet on its free end bends down like a fishing pole when the magnet is attracted.

The glass holder is fitted into an adjustable stand, arranged so that the magnet just clears the surface of the section. When the section is moved by means of the mechanical stage the magnet dips down and touches the specimen if a magnetic grain is brought under it. Since the magnet lies between the polished section and the objective of the microscope it can be observed and, by lowering the focus slightly, the attracting grain can readily be picked out. The magnet is quite sensitive to grains of magnetite and pyrrhotite as small as 0.2 mm. in diameter.

Attempts to apply the method to small magnetite grains in thin sections were unsuccessful because of the thickness of the cover glass, but a stronger magnet (possibly of permalloy), or a tiny electromagnet, might obviate this difficulty.

ELECTROCHEMICAL TESTS.

Methods.—It was found that when a drop of reagent is placed on a mineral in polished section and two platinum electrodes are immersed in the drop, the speed of etching is in general increased. Furthermore, some minerals show characteristic reactions, or give distinctive stains around the anode or cathode.

The method has been used before; Davy and Farnham[1] describe the use of the electric current for speeding up reactions and also note that a plating of metallic copper may be obtained from certain minerals. Schneiderhohn[2] notes the effectiveness of the electric method of facilitating etching and cites examples. Neither describes the individual behavior of more than a few minerals.

This method is capable of a number of modifications, as

1. Both terminals immersed in liquid:
   - *a.* both terminals in contact with mineral surface,
   - *b.* anode raised from grain; cathode in contact,
   - *c.* cathode raised from grain; anode in contact,
2. Only one terminal (*a*, cathode; *b*, anode) inside drop; the other touching mineral outside drop:
   - *a.* The terminal inside drop in contact with mineral.
   - *b.* The terminal inside drop raised from mineral.

The presence of other minerals within the area covered by the drop was found in some instances to cause a considerable variation in the results.

The electro-chemical method promises to be of service in a number of ways:

1. By affording diagnostic reactions of the sort described above.
2. Certain minerals, otherwise difficultly soluble, can be brought into solution in this way for the application of microchemical tests, *e.g.*, enargite and tetrahedrite.

[1] Davy, Myron W., and Farnham, C. Mason, "Microscopic Examination of the Ore Minerals," p. 9. New York, 1920.

[2] Schneiderhöhn, H., "Anleitung zur Mikroscopischen Bestimmung und Untersuchung von Erzen und Aufbereitungsprodukten, p. 120. Berlin, 1922.

3. A qualitative test for copper by electroplating can be made successfully on a number of minerals.

The apparatus used consists of a glass tube into which are sealed a pair of platinum wires. These are connected within the tube, to wires leading from a pair of dry cells through a reversing switch. The tube is mounted in an adjustable lens-holder similar to that used for holding the horseshoe magnet. The glass tube is so mounted as to rotate around its longitudinal axis. Thus one terminal can be raised from the surface of the mineral while the other remains in contact.

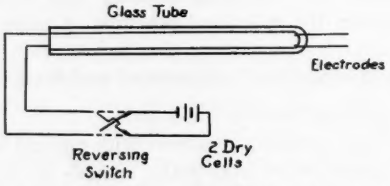

FIG. 2. Electrodes of platinum wire sealed into glass tube. For testing behavior of minerals in reagents under influence of electric current.

Behavior of Minerals.—Although this method has been tried by the writer on a large number of species, it will be necessary to complete the list of rare minerals and to check the behavior of several specimens of each before a table of diagnostic value can be prepared. As the work cannot be continued at the present time, it seems desirable to describe the behavior of a few interesting cases in order to show the possibilities of the method.

Pyrite and marcasite may be quickly distinguished by this means. It is only necessary to place a drop of nitric acid on the polished surface and insert the electrodes, both of them touching the mineral. Pyrite is slightly etched around the cathode without tarnishing, while marcasite takes on a light but distinct tarnish around this pole.

Most copper minerals in nitric acid assume a brown to iridescent tarnish around the cathode or around both poles. In some cases the colors form in concentric circles. Bornite, chalcopyrite,

chalmersite, covellite, enargite, tennantite and tetrahedrite all behave in this manner. If the cathode is raised from the surface of the mineral, though remaining within the drop, it becomes plated with a black coating. If, now, the electrodes are removed, inserted in a drop of nitric acid on a glass slide and the current reversed, the new cathode becomes plated with metallic copper.

With cuprite in potassium hydroxide solution, a tiny bright metallic spot develops under the cathode.

In attempting to distinguish between the numerous light-colored, hard, minerals given in Davy and Farnham's table it was found that only cobaltite underwent a reaction, but this fact alone is of some aid in determination. In nitric acid, with the anode on the surface and the cathode off, a brownish-gray tarnish covers the whole surface of the mineral under the drop. With hydrochloric acid under similar conditions the test is even more distinctive. Under the cathode a light-brown film is formed which disappears with effervescence when the current is reversed.

With native bismuth in dilute hydrochloric acid, a black stain forms around both terminals but is strongest around the anode. On removing the terminals the stain redissolves almost instantly unless the action has been continued long enough to weaken the acid.

LIGHT-ETCHING.

It has previously been pointed out that on exposing polished sections of certain silver minerals to the light of an electric arc the surface takes on a roughened appearance. Guild [3] appears to have been the first to call attention to this phenomenon and Whitehead [4] describes the results of the test as applied to a number of minerals. It has been found that the test succeeds equally well with a broad-filament illuminator used on the large Leitz photographic microscope. While the etching proceeds quite rapidly when the light is focussed through a 4 mm. objective, it

[3] Guild, F. N., "Microscopic Study of the Silver Ores, ECON. GEOL., vol. 12, p. 297, 1917.

[4] Whitehead, W. L., "Notes on the Technique of Mineragraphy, ECON. GEOL., vol. 12, p. 707, 1917.

was found that it could be better observed through the oil immersion objective and consequently this lens was used in the tests. The method was applied by the writer to all the silver minerals in the Murdoch collection at Harvard University and to a few minerals which do not contain silver (in the latter case always with negative results).

With argentite, which is one of the most sensitive minerals, and with most other species that react, the light-etching results in the formation of tiny shining yellowish globules or crystals (the shape cannot be perfectly determined) presumably of metallic silver. The surface roughens, blebs develop first along scratches in the surface and then spread out until they cover the whole field, the distance between the blebs being comparable to their own diameters.

Under strong artificial illumination the blebs begin to appear in less than a second, in the case of argentite, and the reaction is complete at the end of about thirty seconds. With some other minerals the reaction does not become visible until fifteen or twenty seconds have elapsed and, when complete, blebs are widely spaced.

Direct sunlight acts much more slowly than artificial light. Reflected by mirrors and passed through the oil immersion lens, it gives a few silver beads in about 15 minutes. Diffused daylight acts still more slowly if at all. Exposure for two hours to light from the north sky with the 4 mm. objective gave no etching.

A more complete list than that given by Whitehead can now be offered. His results are in general corroborated, though there is a little divergence in some cases. Jalpaite, which he did not test, can be added to the list of the reacting minerals. Stromeyerite, which he reports as negative, was found to vary in different specimens, three reacting while one did not, and even in the same specimen the closeness of spacing of the dots varies considerably in different parts of the field, suggesting a variability in composition.

Cerargyrite, which Whitehead reports as negative, was found to take on a slightly roughened surface so rapidly that a freshly

polished portion of the section must be brought into the field very quickly in order that the change may be observed. After this first flash of roughening the reaction is slow, but at the end of three minutes the surface is more noticeably roughened and a few metallic blebs appear.[5]

Quality of Light.—Argentite and pyrargyrite were tried with different ray filters selected to absorb certain portions of the spectrum but no difference was found in the results given by light of different color-qualities, except that infra-red light of very low visible intensity gives very slow reaction.

Mineral.	Filter.	Time.	Results.
Argentite	58	2 sec.	Blebs begin to appear.
"	70	2 sec.	" " " "
"	88 (infra red)	2 sec.	" " " "
"	None	1 sec.	" " " "
Pyrargyrite	44 A (minus red)	3 sec.	Globules begin to appear.
"	"	1 min.	Parts of area free from blebs but no further action on longer exposure.
"	70	Same as for 44 A	Same as for 44 A.
"	88 (infra red)	60 sec.	No results.
"	"	2 min.	A very few blebs widely scattered.
"	"	5 min.	Several blebs in field but widely scattered.

Apparatus.—The tests given below were carried out on the Leitz large metallographic microscope. An oil-immersion objective was used without color-filter. The distance between set-screws of the illuminator and lens-carriage was 23 cm.; diaphragms of both the illuminator and the reflector were open. With a different set-up the actual speed of the reactions would vary, but by using one of the minerals as a standard, the illuminations may be calibrated.

[5] A striking adaptation of the well known mineralogical test for cerargyrite may be described here. A tiny fragment of zinc filing was placed on a polished surface of the mineral and covered with a drop of water. After a few seconds the cerargyrite beneath it was found to have swelled up forming a raised, cracked surface which, when scraped with a platinum wire, showed the white color of native silver.

Behavior of Minerals.

Minerals Giving Negative Reactions.

The time of exposure was 2 minutes unless otherwise stated.

Andorite	Huntilite	Petzite
Aguilarite	Kalgoorlite	Schirmerite
Calaverite	Krennerite	Stylotypite
Chalcocite (17 min.)	Matildite	Sylvanite
Chilenite	Metacinnabarite	Tapalpaite
Cinnabar (9 min.)	Miargyrite	
Dyscrasite	Naumannite	
Hessite	Native silver	

Minerals Giving Positive Reactions.

Argentite. Always reacts instantly (in less than one second) giving surface covered by closely spaced bands of blebs.

Cerargyrite. Surface roughened instantly. On longer exposure (three minutes) becomes pitted and develops a few metallic globules.

Jalpaite. Reacts slowly, giving relatively small blebs.

Polybasite. Specimens vary and different parts of the same specimen behave differently. Action occurs slowly if at all. Blebs are usually small and widely spaced, sometimes apparently in crystallographic arrangement.

Pearceite. Develops very small blebs confined to certain parts of the field.

Proustite. Reacts slowly; blebs begin forming in half a minute or more; few and widely spaced; one specimen showed blebs only along scratches.

Pyrargyrite. Specimens vary from very slow development of tiny blebs to quick formation of large widely spaced globules.

Stephanite. Action starts fairly quickly (four to ten seconds) and results in either small closely spaced beads confined to certain areas or in larger widely spaced beads.

Stromeyerite. Specimens vary from negative to quickly reacting, but the dots, where formed, are fairly widely spaced.

Applicability.—The method of light-etching, so far as it can be used, has the great advantage that the tests can be carried out in very tiny grains and veinlets which would be practically invisible under the low power of the microscope.

It will be noted that argentite and cerargyrite have characteristic reactions. As for the other minerals that respond; there is so large a variation between different specimens of the same minerals that it is not easy to tell one from another by this method alone. It is convenient, however to be able to divide the silver minerals into three groups.

(1) Those which do not react.
(2) Those which react instantly (argentite and cerargyrite.)
(3) Those which react relatively slowly.

Summary.—All the sulphobismuthides and teilurides, together with native silver and dyscrasite are unaffected by light. The only minerals that are light-etched are Cerargyrite[6] sulphides, sulpharsenides and sulphantimonides; the sulphantimonides tend to react more strongly than the sulpharsenides.

[6] Bromides and iodides were not investigated.

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CLASSIFICATION OF MAGMATIC ORE-DEPOSITS.

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THE ore deposits formed by magmatic differentiation, as is well known, may be subdivided into two groups:

1. Those due to crystallization-differentiation.

2. Those due to liquation, and separated from the silicate magma in the liquid state.

This subdivision is accepted by many authors and may be regarded as being a current one.

Professor Vogt[1] subdivides the first group into two, as follows: (*a*) in the proto-direction with an enrichment of mineral crystallizing at an early stage, or (*b*) in the restmagma direction with enrichment of elements or compounds which do not enter at all, or only to a minor extent, into the first crystallizing minerals.

The same subdivision of the silicate igneous rocks was proposed by Scheumann,[2] who distinguishes: (1) accumulative, and (2) fusive formations, corresponding to Vogt's groups *a* and *b*. These terms seem to be convenient for the designation of corresponding ore-deposits.

Liquation-deposits, according to their origin, may be also subdivided into two groups. The liquation of the original homogeneous magma into ore-magma and silicate melt may be caused either by the change of the physico-chemical conditions, that is to say, of the temperature and pressure, or by the influence of the infusion of country rocks. The possibility of the last mode of differentiation was suggested a long time ago (it was specially pointed out by Loewinson-Lessing and Daly for the silicate eruptive rocks). This seems probable in some cases of the ore melts and silicate liquids. It may be considered as proved in the case

[1] ECON. GEOL., vol. 21, No. 4, 1926.

[2] *Centralblatt für Min., Geol. u. Palaeont.*, Nos. 16–17, Stuttgart, 1922.

of the formation of sulphide melts, and appears as a possible explanation of the separation of the oxide ores.

In accordance with the causes of the liquation two groups of liquation deposits may be distinguished:

1. Liquation deposits in the strict sense of the word, where the separation of the ore melt is a natural process, taking place during the cooling of the magma, as in the silicate-sulphide melts.

2. Syntectic liquation deposits, where the splitting-up of the magma is caused by the infusion of country rock.

We may, therefore, give the following scheme of magmatic ore-deposits:

A. Deposits formed by crystallization differentiation.

(1) Accumulative deposits.
(2) Fusive deposits.

B. Liquation deposits.

(1) Straight liquation-deposits.
(2) Syntectic liquation deposits.

The application of this scheme to some concrete examples may now be given.

DEPOSITS FORMED BY CRYSTALLIZATION DIFFERENTIATION.

Accumulative Deposits.—The most characteristic examples of the accumulative deposits are deposits of chromite in dunite, and platinum deposits. The idiomorphism of the grains of chromite in dunite suggests that this mineral first separated during the crystallization of the rock. Though this statement is not fully incontrovertible, the crystallization of chromite before the final consolidation appears most probable. The forms of the "schlieren" of chromite also correspond to the forms of accumulations of crystals in the magma. This refers, of course, to magmatic chromite deposits, eliminating the more frequent metamorphosed deposits in which the separation of chromite was simultaneous with the serpentinization of the rock.

It is to be noted here that the latest investigations of the native platinum deposits of the Ural make me believe that this separation of chromite and platinum was not a simple process of crystallization from the silicate solution, but, probably, was associated with chemical processes of the splitting of some compounds. However, this decomposition apparently took place before the final crystallization of the magma, and the ore minerals (chromite and platinum) were segregated in the form of the solid phase. Thus, at present, it is most reasonable to refer these deposits to the group of magmatic accumulative deposits.

Fusive Deposits.—It is possible to consider the well studied titaniferous magnetite deposits associated with gabbro-peridotite rocks as representatives of the fusive deposits. Even now, these deposits are frequently considered to be segregations of primary separations,[3] but the study of the texture of ores and enclosing rocks shows that the magnetite within crystallized later than the rock minerals. Duparc has especially pointed out this texture, in which the ore mineral is xenomorphic and appears as a cement among the grains of other minerals, and called it sideronitic texture. In the most typical magmatic deposits of magnetite, in gabbro, there is such a texture. It is unusually well displayed in the deposits of the Ural Mountains (in the domains Laya and Shaitan in the district Kashkanar and Kosvinski Kamen), as well as in the deposits of Välimäki (Finland), Taberg (Sweden) and others. The relations of the ore minerals to the minerals of the rock are particularly distinct in some small magnetite segregations in Kashkanar and Kosvinski Kamen.

The magnetite forms veins in the kosvite which represent the filling of fissures by the material of residual solution squeezed out from crystallizing magma. This last may be observed in the surrounding rock among the crystals of silicate minerals in the form of sideronitic anhedral grains. In this case the differentiation of the magmatic melt, as a residual product, is obvious. The sideronitic texture occurs frequently in plagioclase-bearing rocks of gabbro-peridotitic formation. This texture is common even

[3] For example, see Vogt, in the above cited article.

in so-called ore-gabbros of the Deneshkin Kamen, in which the colored silicates are totally or almost totally absent.

Some volatile constituents must naturally concentrate in the rest-magma. And traces of them are actually found in the deposits. A common phenomenon in these magnetite deposits is the alteration of earlier separated minerals, especially of pyroxene, which is transformed into uralitic hornblende and is sometimes chloritized. The association of these transformations with ore segregations is often very clear. Furthermore, the formation of the magnetite deposits is frequently accompanied by sulphides of iron and copper. These compounds form either impregnations in the ore, or separations in the form of veinlets within it, or occur in the country rocks. An excellent example of this I had occasion to observe in the Ural Mountains in the deposits of Laya and Shaitan domains, as well as in the deposits of Välimäki in Finland.

The fusive deposits may separate from the parent magma under favorable conditions and the ore melt may separate from the silicate constituents in considerable masses and be intruded into the surrounding rocks in the form of dikes. An example of the above, among Russian deposits, is the Magnitnaya in Kusinskaya domain of the South Ural. Titaniferous magnetite forms, in this case, real dikes many feet thick and 5,000 feet long. These dikes dip vertically and cut the amphibolite and amphibolized gabbro. Other well known examples are at Saint Urbain in Quebec, Adirondack region of New York, and Iron Mountain in Wyoming.

LIQUATION DEPOSITS.

Straight Liquation Deposits.—The most typical liquation deposits are of course the magmatic sulphide deposits. These, as it is known, may be distinguished according to the country rock, as: (1) The deposits closely associated with gabbro, norite, etc., for example, the type of Sudbury; and (2) The intrusive pyrite deposits.

Among Russian ore deposits the most typical sulphide mag-

matic deposits are the Norilsk deposits of pyrrhotite containing copper, nickel, and platinum, thus resembling the ore deposits of Sudbury and still more, those of Insizwa, South Africa. It may be that in these deposits the association of the sulphides with the gabbro magma, from which they were separated, is more obvious. The investigations of Urvanzow and Grigoriew show them to exhibit all the characteristic features of magmatic sulphide deposits of this type.

The deposition of sulphide deposits in country rocks at some distance from norite, observed in some Norway deposits, was long ago explained by the mobility of the sulphide magma due to contained dissolved volatile compounds. According to Vogt, the characteristic association of intrusive pyrite deposits with the impregnations of the type of fahlband may be explained by this high mobility of the sulphide magma.

Syntectic Liquation Deposits.—The group of syntectic liquation deposits may be established on the basis of comparative study of the Ural iron deposits of Goroblagodat and Vyssokaya Gora.

This type which I had in view in 1911 [4] receives now, after detailed investigations of Blagodat Mountain [5] (or Goroblagodat), strong confirmations of its importance. Here are deposits of magnetite, partly characterized by the presence of apatite, associated with a syenite magma, and in this case they appear as a result of its contact with the limestone. It seems probable that this type is represented also by the known deposits of Swedish Lapland (Kiirunavaara and others). The following features confirm this:

The deposits of Vyssokaya Gora and Goroblagodat are connected with the same intrusion of syenitic magma and their origin may be explained only by comparative study. The differences observed in these deposits are connected with some differences in the conditions of the formation, and this is what helps to explain the process of the ore segregation of the ores under these different conditions.

[4] *Annales de l'Institut des Mines,* Pétrograd, vol. III., No. 5 (in Russian).

[5] Vera de Dervies, "Recherches géologiques dans la région du mont Blagodat," *Bull. du Comité Géologique,* Léningrad, No. 10, 1924 (in Russian).

Let us consider first the deposit of Goroblagodat. In its central part there is undoubtedly an area of syenitic rocks filled by magnetite originally in a liquid state. The ore contains numerous inclusions of crystals of alkaline feldspar, either in the form of phenocrysts or forming, as it were, fragments of breccia cemented by magnetite. Loewinson-Lessing [6] long ago explained this rock as breccia formed from syenite broken up by the molten magnetite magma. According to Dervies the feldspars of these speckled ores, called in Russian "ospennaya ruda," were formed syngenetically with the ore during the magmatic process.

With regard to the liquid state of the magnetite, many objections have been made, but of late the investigations made by Dervies afford convincing proof for this hypothesis. In addition to the crystals of feldspar, the ore contains also numerous inclusions of rocks, torn off and replaced during the intrusion of the magnetite, such as metamorphosed diabase tuffs cut across by the syenite porphyries and, what is of special interest, inclusions of limestone recrystallized into coarse grained marble with a rim of contact minerals. All these fragments are suspended in the mass of magnetite and seem to have been floating in the molten magnetitic ore at the time of the formation of the ore-body. The flow structure observed in some places also affords evidence of the magnetite having been in a liquid state. The correlations between the ore and syenite porphyries show the subsequent consolidation of the ore-magma. It seems, however, indubitable that they were formed from the same magmatic mass. It is possible to suggest the simultaneous existence of the silicate syenitic magma and of the ore magma at some moment of the differentiation.

Furthermore, recent investigations show that the magnetite magma was apparently similar in its physical properties to pegmatitic magma rich in mineralizing agents. It possessed a high penetrating power and was able to insinuate itself into, and to assimilate the country rock of ancient schists and probably volcanic

[6] *Annales de l'Institut Polytechnique*, St. Pétersburg, vol. VIII., 1907 (In Russian).

tuff masses. These phenomena may be observed in the northern half of the central part of the deposit.

The deposits of the northern part of Goroblagodat have a different character. Here are stratified ore deposits accompanied by contact metamorphic rocks, and to this kind of metamorphism Dervies assigns the formation of this part of the deposit.

The phenomena of contact metamorphism are evident in the deposit of Vyssokaya Gora. The main part of it represents typical contact metamorphic formation, with the development of garnet skarn and with other similar features.

Furthermore, on the Vyssokaya and in its surroundings, are deposits of magnetite lying wholly inside the more or less metamorphosed syenitic rocks; their presence is established by diamond-drilling. It would be more correct to explain such conditions of ore deposition by magmatic formation in the syenite mass similar to that at Goroblagodat. At any rate they differ from typical contact metamorphic deposits lying in the skarns, and I find it difficult to conclude that they are parts of the limestone torn off and transformed into ore by metasomatism during the process of contact metamorphism.

The peculiarities of the deposits of Goroblagodat and Vyssokaya mountains point to the following mode of formation: The presence of the contact metamorphic magnetite deposits proves that in the composition of the original magma there were volatile ferruginous compounds which emanated during the cooling, and produced the reaction with the limestone and the formation of magnetite by metasomatism. But adjacent, and under similar geological conditions at Goroblagodat, may be seen the formation of liquid magnetite melt simultaneously with the syenite magma. It is natural to conclude that the ore melt, which may be seen solidified in the central part of Blagodat, is the result of the same reaction between the ferruginous volatile components of the magma and the limestone, but the magnetite was separated at higher temperatures in the liquid state. It is actually a syntectic liquation process. It is rather difficult to admit it in the case of oversaturated granite magma containing free silica, for then we

might rather expect the formation of lime iron silicates, but it appears possible in syenitic saturated magma. The above suggested hypothesis rests on another reason. The reaction with limestone must necessarily give rise to some lime compounds in the composition of the volatile constituents of the magma. And in fact we see traces of their activity upon the eruptive rock in some of the phenomena of contact metamorphism; they appear as mineralizing agents of the endogene contact metamorphism, that is, of the garnetization of the igneous rock, of the formation of skarn minerals in it, and of similar phenomena of calcification.

Naturally there should be expected the presence of volatile lime compounds in the magnetite ore-magma, formed by the above-mentioned process. And indeed, in addition to the magnetite deposits in syenites north of Vyssokaya and in part at Blagodat, garnetization, and the formation of pyroxene and other metamorphic modifications in the country rock are fairly frequent. At Goroblagodat are other interesting phenomena. Beside the ore-body, the red alkaline feldspar of the syenitic rocks is replaced by greenish scapolite in coarse crystals, sometimes with radial disposition. Is it not the phenomenon of calcification due to the activity of pneumatolitic solutions of the lime compounds? Finally, it is possible to explain the presence of apatite, so characteristic of the deposits of the type (as at Lebiaginsky mine, near Vyssokaya) by the fixation of the phosphorus of volatile compounds, which takes place by assimilation of the lime during the syntectic process. The common presence of the sulphides may be explained by their solubility in the magnetite magma.

Up to now we have discussed only the deposits of the Ural Mountains. They are assigned to one group with the well known deposits of Lapland. Would it not be possible to apply the same syntectic-liquation hypothesis to these latter deposits? The liquid state of the magnetite in the form of melt in these deposits during their formation was demonstrated by Stutzer,[7] and

[7] Stutzer, O., "Die Eisenerzlagerstätten bei Kiruna," *Zeitschr. f. prakt. Geol.*, 1906.

particularly by Geijer [8] and is accepted by almost all authors, but the cause of the separation of the magnetite liquid is not quite clear. It is impossible to leave unnoticed the similarity of this magma to that of the Ural deposits. The ores under consideration are rich in phosphorus, and the deposits as well as the enclosing country rocks, show alteration; at the same time there are formations resembling skarns and in some (Svappavaara) the remains of limestone are present with the phenomena of contact metamorphism, and, finally, they are all associated with syenite magma. The combination of these peculiarities, difficult to explain from any other point of view, appears natural from that of the syntectic-liquation hypothesis.

The peculiar rock from Kiirunavaara, to which Geijer gave the name of magnetite-syenite-porphyry is almost identical with that found in the form of fragments of volcanic breccia in Vyssokaya described by Loewinson-Lessing under the name of ore-porphyry. The occurrence of this last at Vyssokaya enhances still further the resemblance of these deposits to those of Lapland.

All this induces me to believe that the deposits of the Kiirunavaara type are syntectic-liquation deposits, where the ore-magma separated from the parent syenitic magma at depth by reaction with the limestone. Subsequent movement and intrusion of the magnetite magma gave rise to ore deposits that now lie distant from their source, and that renders obscure the features of these deposits, which are sufficiently clear in the deposits of the Ural Mountains.[9]

MINING INSTITUTE,
LENINGRAD, RUSSIA (U. S. S. R.).

[8] Per Geijer, "Igneous Rocks and Iron-ores of Kiirunavaara, etc.," Stockholm, 1910.

[9] The present article had been completed before receiving the paper by Professor J. H. L. Vogt on "The Genesis of the Iron Ore of the Kiruna Type" (*Geol. Förening Förhandl.*, Stockholm, B. 49, H 2, 1927).

The hypothesis of subsidence and resorption or remelting of the first crystallizing minerals, offered in explanation of the genesis of the deposits of the Kiruna type seems to be inadmissible in the case of Ural deposits where the ore is found almost *in situ* of its formation near the contact with the limestone.

ORIGIN OF THE GUNFLINT IRON-BEARING FORMATION.[1]

J. E. GILL.

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INTRODUCTION.

THE Gunflint iron-bearing formation appears in almost continuous outcrop from Nolalu, Ontario, southwest to the International Boundary at Gunflint lake and about 8 miles beyond in Minnesota. It probably also underlies a continuous belt from Nolalu northeast to Loon lake, Ontario, but is only exposed in a few places (Fig. 1). A detailed investigation of that part of the formation

[1] Published with the permission of the Director, Geological Survey of Canada.

between Silver Mountain, Ontario, and Gunflint lake, for the Geological Survey of Canada in 1924,[2] led the writer to a consideration of the problem of the origin of these iron-rich beds.

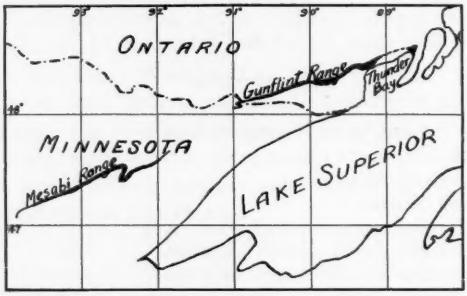

FIG. 1. Index map of distribution of Gunflint formation.

GEOLOGICAL RELATIONS OF THE GUNFLINT FORMATION.

The relation of the Gunflint formation to the other rocks of the district is shown by Table I. Detailed descriptions of these rocks have been published elsewhere.[3]

The Gunflint formation is overlain conformably by the Rove slates, except where the uppermost iron-rich beds have been folded and brecciated by local disturbances. The entire series, in the areas examined, strikes on the average N. 60° E. and dips 5° toward the southeast. Aside from the local folding and brecciation mentioned above, the only marked changes in the distribution of the original beds have been caused by normal or gravity faults. These may be grouped roughly into two systems with strikes north-south and east-west respectively. All have steep dips. The maximum throw observed was 300 feet.

CORRELATION.

The propriety of correlating the Gunflint formation with the Biwabik formation in Minnesota is no longer questioned. The

[2] Field work was supplemented by laboratory studies at Princeton University.

[3] Gill, J. E., Geol. Survey of Canada, Summary Rept. for 1924, part C.

general geological relations, compositions and textures are so similar and so unusual that there is little doubt that they were

TABLE I.

FORMATIONS.

Quaternary	Recent	alluvium
	Pleistocene	clays, sands and gravels
great unconformity		
Precambrian	Keweenawan	diabase sills and dikes
	intrusive contact	
	Animikie	Rove slate Gunflint formation
	great unconformity	
		batholithic rocks, mostly granite
	intrusive contact	
		hornblendite

formed at the same time and were formerly continuous where now they are separated by the Duluth gabbro. The detailed stratigraphic correlation, as shown in Fig. 2, is based primarily on the occurrence of two clearly-defined and continuous beds of algal chert and one of ferruginous "slate." Further details have been discussed in the paper already cited.

INTERPRETATION OF TEXTURES.

For the purpose of discussing their origin, the textures observed in the Gunflint formation are grouped as follows:

1. Original: *a.* Common in normal sediments.
   b. Due to colloidal phenomena.
   c. Due to organisms.
2. Secondary: *a.* Due to regional metamorphism.
   b. Due to contact metamorphism.
   c. Due to weathering.
   d. Due to veining and replacement.

Original Textures.

Those who have made a detailed study of the Biwabik or Gunflint formations have no doubt that the materials composing them

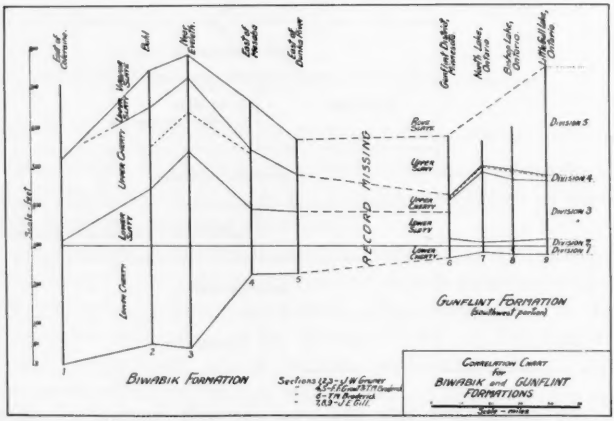

FIG. 2. Correlation chart for Biwabik and Gunflint formations.

are in the main chemical precipitates that, except for local changes due to surface oxidation and solution or contact metamorphism by intrusive igneous rocks, have suffered only minor alterations since their formation. For a rock composed of granules made up of microscopic particles of greenalite or hematite dispersed through microcrystalline chalcedony and set in a groundmass of clear chalcedony, usually slightly coarser in crystallization, no other ex-

planation seems possible. When studied in detail, such rocks bear only slight resemblance to clastic sediments. In fact, material clearly identifiable as clastic is so rare above the basal conglomerate as to be a curiosity.

Textures Common in Normal Sediments.—The basal conglomerate, present throughout most of the areas examined, and up to 2 feet thick, is obviously a clastic sediment. It consists of partially rounded pebbles of the underlying rocks, up to 8 inches in diameter, set in a matrix of finer rock fragments and quartz particles with much chloritic material, probably developed from the ferromagnesian minerals of the underlying rocks. By far the greatest number of the pebbles are milky quartz, sometimes with associated orthoclase. The matrix of the conglomerate passes gradually into altered granite, which in turn gives way to fresh granite. In many places it is impossible to be sure just where the sediment ends and the granite begins.

From the poorly-sorted nature of the material, the lack of rounding of the pebbles, and the fact that they have all been derived from the rocks immediately below the conglomerate, it is clear that no great transportation intervened between erosion and deposition. Again, from the great preponderance of the resistant quartz pebbles, the abundance of finer materials of granite decomposition in the cement, and the observed gradation from the conglomerate matrix to altered granite, it is concluded that this sediment has resulted from the reworking of a residual soil on the pre-Animikie land surface, by the advancing Animikie sea.

Above the basal conglomerate, clastic material is extremely rare. Many of the "slaty" beds contain fragmental particles, that are usually microscopic in size, but may be 2 mm. or more in diameter. These never form the entire bed, but are always associated with chemically precipitated materials identical with those making up the cherty beds (see Fig. 6–*D*). Locally, a granule texture may be observed even in these, but there can be no doubt as to the origin of most of the fragmental particles. Fragments of lava, some of which show minute laths of plagioclase, others of devitrified glass, fresh angular particles of orthoclase, plagioclase

and quartz and an occasional broken flake of mica make it clear that part of these beds is pyroclastic in origin. Some of these minerals, notably the smaller grains of feldspar, show alteration to an amorphous mineral resembling greenalite, or to a matted aggregate of amphibole needles. This may be due to submarine alteration, or halmyrolysis, as defined by Hummel.[4]

Some of the slaty beds may contain some clayey material, but they are so generally iron stained that the presence of such fine material is difficult to determine without chemical analyses.

In Division 4 intraformational conglomerate occurs quite generally. Fragments of banded chert (which may or may not show algal structures), cherty taconite, hematite, magnetite, or both oxides appear in a matrix of oolitic chert. The fragments are angular or only slightly rounded, and the relations are such that they clearly represent portions of beds broken up, but not transported any great distance from their original positions (see Fig. 6–*A*). Cherty taconite[5] pebbles usually show more rounding than the others, probably because they were less consolidated at the time of the disturbance. These conglomerates are believed to have formed when the seas were shallower than was usually the case during the iron formation period in this area. The actual breaking up of the original cherty or oxide-rich layers was probably accomplished by waves, perhaps during storms.

Some of the carbonate-rich beds have textures resembling those of ordinary limestones and they therefore are considered to have had a similar origin.

Textures Due to Colloidal Phenomena.—In recent years there has been an increasing tendency amongst geologists to ascribe the formation of more or less spherical aggregates of amorphous or finely crystallized substances to colloidal phenomena. Though

[4] Hummel, K., "Die Entstehung eisenreicher Gesteine durch Halmyrolyse," *Geol. Rundschau*, B. 13, p. 42, 1922.

[5] "Taconite," as here used, refers to rocks with a granule texture. It is used with qualifying descriptive terms which always refer to the composition of the granules. Thus "greenalite taconite" is a rock composed of granules in which greenalite is the most important constituent other than chalcedony, which is present in practically all cases. The groundmass is spherulitic or microgranular chalcedony in most instances.

the information available regarding the conditions surrounding the coagulation of colloidal solutions is far from satisfactory and many apparently contradictory statements are encountered in the literature, the fact has been established that, under certain conditions of coagulation from the colloidal state, many inorganic substances form more or less spherical, loosely aggregated masses without the aid of organisms.

Schade,[6] working with urinary calcula and their materials, showed that the formation of such concretions is largely colloidal and is due to dispersed material passing from the emulsoid to the solid state. If the substance has a strong tendency toward crystallization and is pure, the internal structure is radiating and fibrous. If there is no strong tendency toward crystallization, and impurities are present, a concentric structure is more commonly developed.

Lehmann[7] found that globular forms are characteristically developed in precipitates which lack a strong crystallizing tendency and in other precipitates they are often intermediate steps toward the development of crystal form.

Link[8] has shown experimentally that calcium carbonate, when precipitated as fine mud, assumes an oölitic structure and Vaughan[9] obtained similar results. Bucher[10] produced oölitic structures in other inorganic substances without the direct or indirect help of organisms. Tarr[11] found that when silicic acid was added to a solution of NaCl with the same concentration of total solids as sea water the gelatinous precipitate obtained "coagulated into small globules in the bottom of the container."

[6] Schade, H., *Zeit. f. chemie u. Ind. d. Koll.*, 4, 1909, pp. 175–180 and pp. 261–266.

[7] Lehmann, O., "Flussige Kristalle sowie Plastizität von Kristallen im Allgemeinen, molekulare Umlagerungen und Aggregatzustandsanderungen," Leipzig, 1904. Cited by Van Hise and Leith, U. S. G. S. Mon., LII., p. 525, 1911.

[8] Link, G., "Die Bildung der Oolithe und Rogensteine," *Neues Jahrb.*, Beilage Bd. 16, pp. 495–513, 1903.

[9] Vaughan, T. W., "Remarks on the Geology of the Bahamas, with Special Reference to the Origin of Bahaman and Floridan Oölites," Paper from the Tortugas Lab., Carnegie Inst. Wash., 1914.

[10] Bucher, W. H., *Bull. Geol. Soc. Am.*, 1918, p. 103.

[11] Tarr, W. A., "Origin of Chert in the Burlington Limestone," *Am. Jour. Sci.* (4), vol. 44, 1917.

Van Hise and Leith [12] succeeded in producing artificial greenalite and, speaking of the precipitates of greenalite and associated silica formed in their experiments, they say, " . . . (they) first constitute a flocculent precipitate. As this precipitate settles, a granular structure practically identical with that observed in the Mesabi slides is developed."

Bucher believes that in practically all cases oölitic and spherulitic grains form in free suspension " by at least one of the constituents changing from the emulsoid state to that of the solid, (and) that the spherical shape of the grains is due to the tendency of the droplets forming during this process of separation to coalesce."

Several writers [13] have expressed the opinion that organisms have played a part in determining the shape of spherites and granules, but where organisms are undoubtedly proved to be present, their inclosure by the granules can usually be just as readily explained as purely fortuitous. Organisms have, however in many cases, played an important part in the formation of granules by causing the separation of fine colloidal " muds " or gelatinous precipitates which then collect into more or less spherical forms or " droplets " and later crystallize to form spherites, spherulites, or granules with no regular internal structure, according to the nature of the materials involved.

The writer believes that the textures and relations of the granules, so abundant in the rocks of the Gunflint and Biwabik formations, support the idea that they formed by the coagulation of emulsoids or suspensoids, that a portion of the coagulum, which was partly or wholly gelatinous (silica, greenalite, ferric hydroxide) but may have been partly granular (carbonates, ferric oxide) collected into more or less spherical forms under the influence of surface tension, after the manner characteristic of such precipitates, and that subsequent dehydration and partial crystal-

[12] U. S. G. S. Mon., vol. LII., p. 522 and Plate XLII., B, 1911.

[13] Brown, T. C., " Origin of Oölites and Oölitic Textures in Rocks," *Bull. Geol. Soc. Am.*, vol. 25, p. 772, 1914.

Gaub, F., " Die Jurassischen Oolithe der Schwaebischen Alb," *Geol. und palaeont. Abh.*, N. S., IX. (1910), Heft 1.

lization developed textures which have been retained in many cases up to the present time in essentially their original condition. Usually, gelatinous silica was much in excess of the other constituents and this formed the groundmass in the majority of the rocks.

Organisms may have played a part in the precipitation, but that they were not essential to precipitation and that they probably did not determine the forms of the granules is indicated by the fact that granules were observed to have developed under conditions which seem to have made the existence of the organisms responsible for the algal structures impossible. This point is discussed further on a later page.

The granules and nodules which, from their internal textures seem to have been altered but slightly from their original condition, may be grouped as follows:

A. Greenalite granules.
B. Hematite granules and nodules.
C. Chalcedony granules.
D. Spherites.
E. Carbonate spherulites and nodules.

A. Greenalite granules are seldom homogeneous. Most of them contain a certain proportion of microgranular chalcedony, that appears in variable distribution, producing a variety of internal textures. Granules consisting entirely of greenalite are comparatively rare and many of those which appear homogeneous at low magnifications show a definite internal texture under higher power lenses, due to the presence of small amounts of admixed silica.

By far the most common internal texture appearing in these granules consists of small spherical or almost spherical segregations, in many cases surrounded by a ring of clear chalcedony, the change from the greenalite center to the clear chalcedony being gradational and the chalcedony often found radially crystallized about the greenalite core (see Fig. 3*B*, *D*, *E*. *F*). The closeness of packing of these spherical segregations varies in different granules or in different parts of the same granule. Some of the

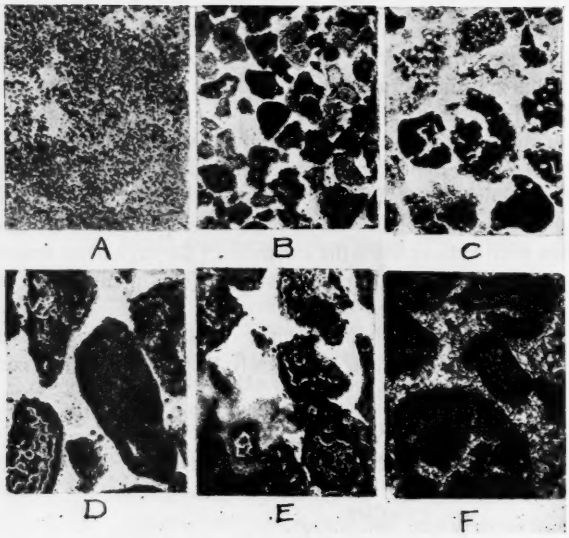

FIG. 3. *A*. Greenalite forming microscopic, more or less spherical segregations in chert. Division 5, south of Little Gull Lake, Ontario. × 40.

B. Greenalite taconite with granules composed of minute spherical segregations of greenalite similar to those in *A*. A few of these appear isolated in the groundmass. Division 3, Silver Mountain, Ontario. × 13.

C. Almost homogeneous greenalite granules and others showing segregations of clear silica with interstitial greenalite. The groundmass is microgranular chalcedony. Division 3, North Lake, Ontario. × 13.

D. The large, dark greenalite granule, though seemingly homogeneous at low magnifications, is in reality made up of spheres of greenalite with interstitial chalcedony, as are those at left. Division 3. × 40.

E. Calcite (dark gray) replacing spherulitic silica in greenalite taconite. Division 3, Little Gull Lake, Ontario. × 40.

F. Contraction fissures in homogeneous greenalite granule, filled by chalcedony with a texture identical with that of the groundmass. Division 3, Little Gull Lake, Ontario. Crossed nicols. × 40.

apparently homogeneous granules mentioned above are seen to consist of closely packed segregations of this sort when examined at high magnifications. In some granules they may be seen to have partially or wholly coalesced to form irregular patches of greenalite (Fig. 3*D*). Many of these, if cut in different directions, would doubtless show evidence of their composite nature.

The rock whose texture is shown by Fig. 3*A* is thought to throw some light on the origin of these peculiar textures. In this rock, somewhat similar, though smaller segregations appear, showing no aggregation into granules. They exhibit the same outward gradation to clear chalcedony and often form centers for silica spherulites. These are thought to represent small blebs or droplets formed as gelatinous greenalite separated from colloidal solution. In this instance, conditions were not favorable for aggregation of these minute droplets into granules, but in the majority of cases, such aggregation did occur. On the fluidity of the blebs would depend the completeness of coalescence, and hence the degree to which the composite nature is revealed in the present granules. If partially dehydrated before aggregation, they would tend to retain their identity. Further dehydration after aggregation, would probably tend to emphasize the individuality of these components and the minute openings between the spheres caused by shrinkage, would be filled by silica which was greatly in excess, just as the interstices between the granules and the contraction fissures in the granules are so filled. Some of the segregations served as nucleii about which silica spherulites developed. That the clearness of this internal texture is due in part at least to contraction by dehydration is indicated by the rarity in these granules of irregular contraction cracks which are so common in most others (cf. Figs. 3*C*, *F*; 4*A*, *C*). Silica spherulites, in growing outward from a center seem, in some instances to have thrust aside particles of impurities to some extent and this has increased the sharpness of the texture.

Spurr [14] and Leith [15] both mention these textures and have ex-

[14] Spurr, J. E., "The Mesabi Iron-bearing Rocks," Minn. Geol. and Nat. Hist Surv., Bull. X., Plate VI., Figs. 1 and 2, 1894.

[15] Leith, C. K., U. S. G. S. Mon. 43, p. 117 and Plate XIV., *A* and *B*, 1903.

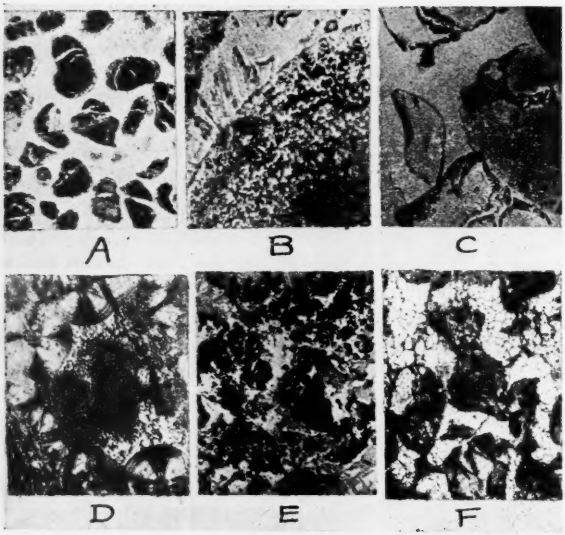

FIG. 4. *A*. Typical hematite taconite. Granules consist of extremely fine particles of hematite dispersed through chalcedony. The groundmass is chalcedony. Note the variable concentration of the hematite particles. Division 5, North Lake, Ontario. × 10.

B. Showing the margin of one of the granules in *A*. Note the closer packing of the hematite particles toward the center of the granule. × 300.

C. Granules in hematite taconite, showing a tendency toward segregation of hematite particles along granule boundaries and along the walls of contraction fissures. Division 5, Little Gull Lake, Ontario. × 40.

D. Spherulites of silica, found most commonly about the margins of granule-like segregations of impurities such as iron oxides. Division 5, Silver Mountain, Ontario. Crossed nicols, × 40.

E. Intergrowth of magnetite (dark gray) and hematite (light gray), associated with calcite (etched black). Division 3, Little Gull Lake, Ontario. × 62. Polished specimen.

F. Contact metamorphosed greenalite taconite. Granules now consist of matted aggregates of iron-rich silicates, mainly amphiboles. Note the development of amphiboles between the quartz grains of the recrystallized groundmass. Division 3, Bishop Lake, Ontario. × 40. Ordinary light.

cellent illustrations of them in their reports. In those figured by Leith, the original greenalite nucleii of the silica spherulites have been altered to iron oxides, giving a somewhat different appearance to that observed in the fresh granules. The silica has probably also been recrystallized. He states that similar structures in the Clinton iron ores are "clearly due to the replacement of a shell with regular structure." The similarity seems somewhat remote to the writer, since the feature which proves an organic origin for the structures in the Clinton ores, that is, regularity in the arrangement of the "cells" or comparments, is absent in these granules. The uniformity in size of the minute segregations is just as readily explained as due to the general uniformity of conditions of coagulation as to control by organisms. Approximate uniformity of grain size is characteristic of all granular precipitates and is one of the marked characteristics of oölitic rocks in general.

Gruner[16] attributes these structures to the work of microorganisms, calling them "cell structures." There is very little evidence to support this view, however.

In many other granules, less regularity in the distribution of greenalite and silica is observed, giving textures such as those shown in Fig. 3*C*, due probably to a segregation of the silica and greenalite during dehydration and crystallization of the silica.

B. Granules consisting solely of hematite are extremely rare and the usual type consists of microscopic particles of hematite, uniformly or irregularly dispersed through chalcedonic silica (Figs. 4*A*; 5*D*). Even those that appear to consist of solid hematite at the center, are often seen to grade out into the chalcedony of the groundmass toward their borders (see Fig. 4*B*). A tendency toward segregation of these fine particles about the borders of granules and along the walls of contraction cracks is often observed (Fig. 4*C*).

The original precipitates from which these granules developed probably consisted of gelatinous silica and hydrated ferric oxide. Dehydration to anhydrous ferric oxide may have followed rap-

[16] Gruner, John W., "Organic Matter and the Origin of the Biwabik Iron-bearing Formation," ECON. GEOL., vol. 17, p. 415, 1922.

idly, since W. Spring [17] has shown that freshly precipitated ferric hydroxide undergoes spontaneous dehydration while still in contact with water, particularly if the latter is saline. The various present arrangements within the granules was probably developed during the dehydration and crystallization of the silica which is now microcrystalline chalcedony of extremely fine grain. Where a coarser grain has been developed in the chalcedony, the hematite usually shows signs of recrystallization also, sometimes appearing as platy crystals. Partial alteration to magnetite may also have occurred in such cases and the two minerals may appear intergrown with one another.

Larger nodules of hematite, sometimes approximately circular or oval in section, but usually quite irregular, occur in the magnetitic chert beds of Division 3, at Bridge Bay, Ontario. The microtextures of some of these show that they were originally precipitated in much their present form, for it is difficult to account for flocculent, more or less spherical aggregates of minute hematite particles, such as those shown in Fig. 5*B*, on any other hypothesis. In the majority of cases, the original nature of these nodular concentrations has been obscured by recrystallization of the original hematite to intergrowths of magnetite and hematite. Somewhat similar, though usually more regular nodules have been described by Grout and Broderick,[18] who regard them as true pebbles resulting from the breaking up, in shallow seas, of thin beds enriched by re-solution of silica. The writer observed pebbles obviously formed by the breaking up of beds originally rich in hematite, in the intraformational conglomerate associated with the upper layer of algal chert but at no other horizon.

These hematite dispersions in chalcedony have been thought by some writers to have resulted from the alteration of original greenalite granules, but the internal textures of these granules are so different from those commonly observed in greenalite

[17] "Uber die eisenhaltigen Farbstoffe sedimentaerer Erboden und uber den wahrscheinlichen Uhrsprung der rothen Felsen," *Neues Jahr. Min.*, vol. I., pp. 47–62, 1899.

[18] "Magnetite Deposits of the Eastern Mesabi Range," Minn. Geol. Survey Bull. 17, p. 43, 1919.

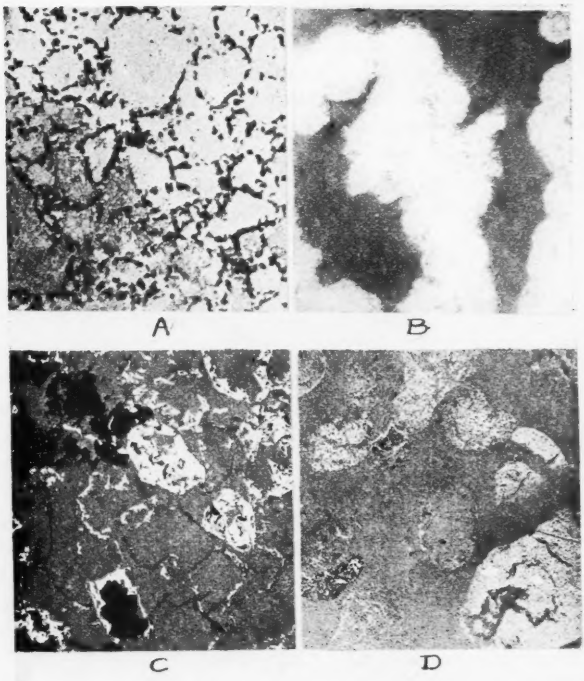

FIG. 5. *A*. Showing two generations of carbonates. The black mineral, appearing as a rude network, is siderite. The dark gray mineral, partially replacing the light gray chert, is calcite. Division 3, Little Gull Lake, Ontario. × 13.

B. Flocculent aggregates of hematite particles from one of the hematite-magnetite nodules in the middle part of division 3, North Lake, Ontario. Usually these have been altered to intergrowths of magnetite and hematite and such alteration was observed in other parts of this section. Polished section. × 220.

C. Magnetite and hematite as traceries about the margins of some granules and forming the major part of others. Calcite (etched black) is present, partly replacing chert (gray). Division 3, Bishop Lake, Ontario. Polished section. × 24.

D. Polished section of hematite taconite. The large granule would appear opaque in thin sections, but on polished surfaces the finely distributed chalcedony is visible. Division 5, North Lake, Ontario. × 32.

granules that this explanation is thought to be improbable. Unless the change took place shortly after deposition and before crystallization of the silica, it should be indicated by the internal textures of the granules, for it would involve the formation of a second generation of silica and a decrease in volume. The texture of this second generation of silica would probably differ from that of the original chalcedony. Variations in the extremely fine, microgranular texture of the chalcedony in the granules is seldom observed.

Considerations of distribution bear out the above conclusions. Granules of this type are confined to a thin band, varying from 20 to 60 feet in thickness, occurring immediately above the upper layer of algal chert, and this band is persistent throughout the length of outcrop examined. In the vicinity of North Lake, beds of this type are interlayered with others of different texture, and they seem to become progressively fewer toward the west. In the Mesabi district the writer observed similar beds near the base of the "Lower Cherty Division." Gruner describes this under the name of "red basal taconite" and says of the group, ". . . [it] is easily traced from Aurora to the west end of the range. . . . In spite of its gradual transition downward into the basal conglomerate and upward into the cherty beds, it is not easily overlooked because its color is so conspicuous and there are no other similar beds in the "Lower Cherty division." Thus it is clear that beds of this type form well defined stratigraphic groups, persistent over large areas horizontally. Within a few feet above and below, almost equally persistent beds of greenalite taconite appear and it is difficult to see how one part of the series could have suffered alteration, whereby hematite was developed from original greenalite, while the beds above and below escaped entirely, unless the change is considered to have occurred almost contemporaneously with deposition. In some instances, such contemporaneous alteration may have occurred, but in general, such an assumption introduces an unnecessary complication, since hydrated ferric oxide may form as a direct chemical precipitate just as readily as ferrous silicate.

As indicated on a later page, higher temperature probably favors the development of hematite oölites in place of silicates such as glauconite, and it is therefore thought that such a variation is indicated by these beds, accompanied, perhaps by shallow water conditions, as suggested by the presence of algal chert and intraformational conglomerates directly below.

C. In the purer cherty beds, granules of almost pure chalcedony are frequently observed. In outward form and size they resemble typical greenalite or hematite granules and in fact they are often distinguished by the presence of a small amount of green pigment, probably greenalite, too fine to be distinguished under the microscope. In other instances, they can be detected only between crossed nicols, when they are seen to possess a texture slightly different from that of the groundmass. Tarr[19] observed similar structures in the chert within the Burlington limestone and his experiment by which he showed that precipitated gelatinous silica assumes such globular forms, under certain conditions, demonstrates the way in which these granules may have been, and probably were, formed.

D. Spherites were only observed to have formed in association with algal chert and intraformational conglomerate (see Fig. 6–*A, B, C*). Both of these rock types are probably indicative of shallow water conditions, and the conclusion seems to be warranted that such conditions were requisite for the formation of the spherites.

Van Hise and Leith[20] regarded them as concretions developed during the alteration of cherty siderite. In the case of a 1.5 ft. bed occurring in the middle of Division 4, from North Lake to beyond Mink Mountain, a distance of approximately 25 miles, and consisting entirely of such spherites set in a groundmass of chalcedony, there seems to be no question as to the primary origin of the main features of the present textures. Siderite was nowhere observed to form part of this bed, nor was any evidence found to support the assumption that it had been present. The

[19] Tarr, W. A., *op. cit.*, p. 437.
[20] U. S. G. S. Mon. LII., Plate XLII., *D*, 1911.

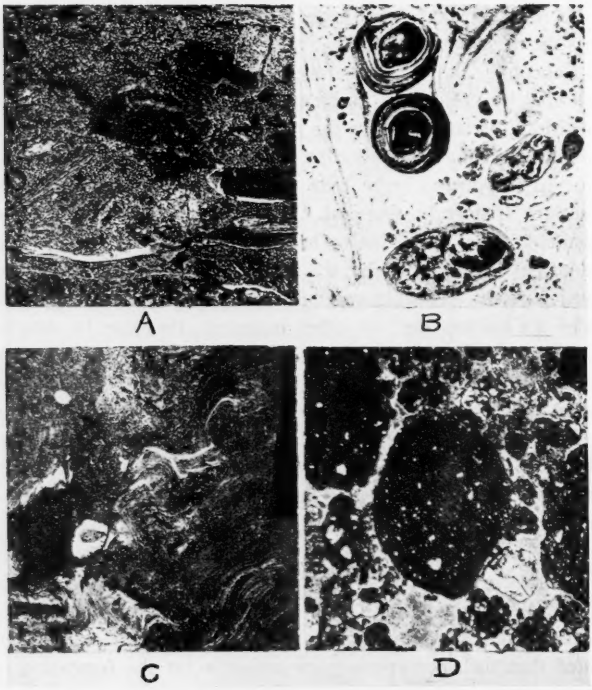

FIG. 6. *A*. Introformational conglomerate, associated with and containing fragments of algal chert. The minute spherites characteristically weather white, giving a speckled surface. Silver Mountain, Ontario. × ¾.

B. Spherites associated with algal chert. The cores of the spherites resemble ordinary granules. The irregularly-shaped black areas are magnetite, which in most instances has been formed by alteration of greenalite or hematite. Division 1, Little Gull lake. × 13.

C. Vertical section of contorted chert, showing wavy lining and associated oölite. Division 4. Silver Mountain, Ontario. × ½.

D. Tuffaceous taconite. The granules are composed of a dark green chloritic substance resembling greenalite, with fragmental particles. The groundmass is chalcedony or a matted aggregate of amphibole needles. Division 5. Silver Mountain, Ontario. × 13.

rhythmic, concentric banding is due to the presence of greenalite and hematite in all cases, though occasionally one may be present to the exclusion of the other. They show contraction cracks filled by chert similar to that of the groundmass, as do the other granules, and in short, it is inconceivable that there has been any considerable alteration of these spherites since the original consolidation of the bed.

Most of them have a core resembling granules of the normal type, without any regular internal structure. It therefore seems probable that disturbances in shallow water have kept them in suspension, or that they have been swept up after original deposition and had additional layers of silica, greenalite and (or) hematite added, the banding being due to rhythmic precipitation of these substances. Usually both hematite and magnetite are present and the oxides in most cases seem to bear a definite relation to the greenalite concentrations. It is quite possible that they have developed, in part at least, by partial decomposition and oxidation of greenalite. If it is assumed that greenalite and silica were the only original constituents and that the oxides have developed by alteration of the greenalite, it is possible that the banding was developed by impregnation of globular masses of silica gel by iron salts from without, after the manner of formation of Liesegang rings. However, this is thought to be less probable than the first explanation because of the fact that the banding is usually confined to the outer half of the spherites, leaving a core about the size of the normal granules (see Fig. 6*B*).

E. Carbonate nodules varying in size from 1/10 inch to 3/4 inch diameter, are extremely abundant in certain beds of Division 3, particularly in the vicinity of Bishop Lake. From their distribution, confined to certain definite horizons, and outward form, usually more or less spherical, it seems clear that they were present in the beds as first deposited in essentially their present form. Most of them contain a small proportion of iron and a few seem to be dominantly $FeCO_3$, but in by far the most of them, $CaCO_3$ is the most prominent molecule. Some of them show a distinct spherulitic structure. Probably most of them originally possessed

such a structure, but in many cases recrystallization has occurred and they now consist of larger, interlocking grains, or a single large individual.

Smaller spherulites of siderite occur in the lowermost beds of Division 3. Groups or strings of these appear to have developed interstitial to granules of almost pure chalcedony in some instances (Fig. 5*A*). They probably formed in much the same way as the larger nodules, by coagulation of colloidal carbonates, but in this case, the amount of carbonate precipitated was much less.

Textures Probably Due to Organisms.—Many writers on the Algonkian of the Lake Superior region have mentioned and described structures believed to be organic in origin.[21] Some of these are generally accepted as organic, others are not. None has been definitely proved to be due to organisms.

Recently Gruner has laid great stress on the presence of organic remains in the Biwabik formation. He believed that organisms played an important part in the precipitation of the iron-bearing minerals and silica, which make up the bulk of the formation.[22] In the report cited, he describes bacteria, bacilli and algæ and presents many excellent photographs in support of his statements. Still more recently Hawley has shown how forms similar to many of those described and pictured by Gruner may be reproduced by inorganic processes (osmotic growths).[23]

The writer believes that the "algal structures" first described by Grout and Broderick are most probably organic in origin, mainly from considerations of distribution and their resemblance to certain cryptozoöns.

The relations south of Little Gull Lake, Ontario, are instructive in this connection. There, a basaltic lava is present at the base of Division 4. Where this is present, the usual chert with algal structures gives way to chert with similar fine red and white lining or banding arranged parallel to the normal bedding of the

[21] Leith, C. K., U. S. G. S. Mon. XLIII., p. 117, 1903. Cayeux, L., *Compt. rend.*, vol. 153, pp. 910–912, 1911. Grout and Broderick, *Am. Jour. Sci.*, vol. 48, p. 199, 1919. Broderick, T. M., Econ. Geol., vol. 15, p. 433, 1920.

[22] Gruner, John W., Econ. Geol., vol. 17, pp. 407–460, 1922.

[23] Hawley, J. E., *Jour. of Geol.*, vol. XXXIV., pp. 441–461, 1926.

sediments and exhibiting none of the contortions characteristic of the algal chert. Algal structures begin to appear in the chert beyond the edge of the flow, and, in exposures a mile distant, the usual variety of forms and sizes are present. It seems certain that in this place the lava flow was responsible for the absence of these peculiar structures. If it be granted that they were formed by organisms, the obvious explanation is that the high temperature in the vicinity of the lava rendered their existence impossible. However, since there is no diminution in the thickness of the banded chert, it seems clear that these organisms played no essential part in the precipitation of the silica, greenalite or hematite. Granules are present in about the usual abundance, and it seems improbable, therefore, that the formation of the granules, or the formation of the so-called "cell structures" within the granules was dependent upon the presence of organisms.

Other structures were observed that are suggestive of organic forms, but there is less to support the hypothesis in these cases than for the "algal structures."

Secondary Textures.

Textures Due to Regional Metamorphism.—The presence of magnetite and small amounts of amphiboles within the granules has been found to be quite general throughout the Biwabik formation. They seem to be somewhat less prominent in those parts of the Gunflint formation not affected by igneous intrusions. Both of the above minerals are commonly considered to form characteristically at high temperatures and, in the absence of extensive igneous intrusion, their formation has usually been explained as due to loading by younger sediments.

In the Gunflint formation, though a small amount of alteration of this kind may have been effected by the higher temperatures and pressures due to loading, by far the greater part of the observed recrystallization and development of new minerals obviously has been due to metamorphism by and during the intrusion of the diabase sills.

Textures Due to Contact Metamorphism.—The principal

changes in the iron formation adjacent to diabase sills have resulted from the development of amphiboles and magnetite in place of the original minerals (Figs. 4*E, F;* 5*C*). There is nothing to indicate any considerable contribution of materials from the magma itself. The present textures and compositions can be accounted for by simple recrystallization and rearrangement of the elements originally present, to form new molecules. Small amounts of pyroxene and epidote are present locally, but are quantitatively unimportant. The extent to which the original textures of the beds have been destroyed by the above alterations is usually a function of the size of the sill and the closeness of the bed to the sill margin.

Textures Due to Weathering.—Weathering has caused decomposition and oxidation of siderite and greenalite to depths of from a few inches to several feet. The concentration of iron by solution of silica has, in all cases observed, been negligible, but this is not necessarily true of the low lying portions of the formation, where residual concentration of iron due to leaching of silica may have occurred locally. Such areas are now covered by drift and recent alluvium of varying thickness.[24]

Textures Due to Veining and Replacement.—Veining by chert is quite general throughout the formation. Obviously such veinlets, which are usually discontinuous and confined to a single bed, represent cracks formed in various ways and filled by silica carried in solution, probably from the overlying beds. Goethite and limonite were observed frequently in similar relations and apparently they have formed by similar processes. Magnetite in veinlets is in part formed by alteration of goethite, probably during the intrusion of the sills. In part it is associated with amphiboles and in such instances, it probably formed directly through the agency of magmatic emanations at the close of the Keweenawan.

Quartz, quartz-calcite, and quartz-calcite-barite-fluorite veins appear at a number of points cutting the iron formation. They are generally considered to have formed during the prolonged pe-

[24] For a discussion of the economic possibilities, see Gill, J. E., *op. cit.*, p. 82.

riod of igneous activity that occurred toward the close of the Keweenawan. Some of them are several feet wide. Locally replacement of the wall rock by calcite and quartz has occurred hand in hand with vein filling.

EARLIER VIEWS CONCERNING THE ORIGIN OF THE BIWABIK AND GUNFLINT FORMATIONS.

Many different opinions have been expressed as to the nature of the original minerals in these formations and the way in which they have been precipitated and subsequently altered. The most fundamental point of controversy, however, has been source of the iron and silica, found in such exceptional amounts in both.

Spurr in 1894 first elaborated a theory to explain the origin of the Animikie iron formations, basing his views on a detailed study of the Mesabi district. He concluded that they originated in essentially the same way as modern glauconite deposits and followed Murray and Renard [25] in the interpretation of the conditions and reactions involved. In view of the variation in the published analyses of glauconite at that time, the deficiency of potash in the green glauconite-like mineral so prominent in the Biwabik formation was not considered sufficient basis for naming a new species.

Leith [26] in 1903 assembled the data then available regarding the composition of glauconite, supplied new analyses of the Mesabi mineral, and concluded that the latter is sufficiently different from typical glauconite to be called by a new name, "greenalite." He also showed that the explanation offered by Murray and Renard for the formation of modern glauconite deposits is not applicable without much modification to the Mesabi deposits and concluded

> . . . that the greenalite granules may possibly have developed directly from the abstraction, through the agency of organisms, of iron from solution in sea water, whence it was contributed in solution.

Subsequent writers have usually mentioned the similarity between greenalite and glauconite; some have admitted a probable

[25] Murray and Renard, "Deep Sea Deposits."
[26] Leith, C. K., U. S. G. S. Mon. 43, 1903.

similarity in the conditions of formation, but the analogy has not been pursued further.

Two theories, strikingly opposed to one another have arisen entirely independent of studies of glauconite deposits. These are:

1. Direct contribution of iron salts and silica from magmas, or by reaction of sea waters upon hot lavas.

2. Derivation from the continents as a result of weathering and solution, transportation by rivers to the sea and deposition there with or without the aid of organisms.

Van Hise and Leith [27] have been the chief supporters of the direct contribution hypothesis. After assembling and discussing at length all the data available regarding the several Lake Superior iron formations, at the time of their writing, they conclude that

> . . . ordinary processes of weathering, transportation and deposition of iron salts from terranes of average composition were as effective in the Precambrian of the Lake Superior region as in other times and places, but these processes account for only thin and relatively unimportant phases of the iron-bearing rocks.

Because of the close association of iron-bearing sediments with contemporaneous basic eruptive rocks in the Lake Superior region and in other parts of the world, the richness of these eruptive rocks in iron salts, and the probable derivation of the upper Huronian slates associated with the iron-bearing formations from the eruptions, they conclude that

> . . . The iron salts have been transferred from the [basic] igneous rocks to the sedimentary iron-bearing formations partly by weathering when the igneous rocks were hot or cold, but the evidence suggests also that they were transferred partly by direct contribution of magmatic waters from the igneous rocks and perhaps in small part by direct reaction of the sea waters upon the hot lavas. . . . In general the parts of the iron-bearing formations originally consisting of carbonate seem to be related to the indirect contribution from the igneous rocks through the agency of weathering, and the parts of the iron-bearing formations originally consisting of greenalite or iron silicate seem to have been contributed in the main directly to the waters without intervening atmospheric or organic agencies.

[27] U. S. G. S. Mon., vol. 52, pp. 499–529, 1911.

They were able to synthesize a substance resembling greenalite in the laboratory by reaction between ferrous sulphate and silicates of the alkalies and also to reproduce certain other reactions which they believed to have been involved in the development of the iron formations.

In the light of more recent information, Gruner [28] comes to a different conclusion. He believes that the iron and silica of the Biwabik formation have been derived from the land and transported to the sea by rivers rich in organic matter. His main reasons may be summarized as follows:

1. Serious chemical difficulties are involved in the direct contribution hypothesis, especially in accounting for formations as uniform and extensive as the Biwabik and Gunflint formations.

2. The Amazon at present carries sufficient iron and silica in solution to supply an amount equivalent to that in the Biwabik formation in 176,000 years.

3. A steady supply of material over a long period would be assured by such a source.

4. Considerable amounts of iron and silica are retained in colloidal solution for prolonged periods even when mixed with sea water, if organic colloids are present.

5. The Biwabik and Gunflint formations show no signs of volcanic disturbances.[29]

6. Lavas were extruded during Keewatin time in greater quantity than during any other succeeding period, yet the greatest development of iron-bearing formations occurred during the Upper Huronian. This suggests, at least, that these lavas were the source of iron-bearing sediments not so much during the time of their extrusion as during their exposure to weathering much later.

7. Other large iron-bearing formations exist that are not associated with large masses of contemporaneous basic igneous rocks, the Itabira formation of Brazil, for instance.

[28] Gruner, John W., *op. cit.*

[29] One lava flow and considerable pyroclastic material in the Gunflint formation show that local volcanism occurred in the areas examined by the writer.

GENERAL CONSIDERATIONS.

Extensive iron-rich sedimentary deposits are known to have formed in all periods following the Cambrian. These include deposits in which glauconite, hematite, limonite, thuringite, viridite, bertherine, etc., may be the principal iron-bearing minerals. All occur in essentially the same stratigraphic relations, interbedded with normal sediments. These bear no conspicuous relation to vulcanism and are apparently normal results of sedimentary processes as we know them today. This statement is well illustrated by the distribution of modern glauconite deposits, which appear about the coasts of all the continents in the tropical and temperate zones.[30]

There is nothing to indicate that natural processes in the Precambrian differed in any essential way from those operating in succeeding epochs and at present. All of the ordinary types of sedimentary rocks are found in the Precambrian. If the uniformitarian principle is to be maintained, the extensive sedimentary iron deposits which formed then must be considered at least in part analagous to modern glauconite deposits and to the other iron-rich sedimentary deposits mentioned above.

The principal objections to the hypothesis of a glauconite-like origin for the Lake Superior iron-bearing formations have been:[31]

(*a*) The theories for the formation of glauconite do not satisfactorily explain the formation of the Lake Superior deposits.

(*b*) The exceptional freedom from clastic material in the Biwabik formation.

(*c*) No glauconite deposit is known with a thickness nearly equal to that of the Biwabik formation.[32]

These objections are not insuperable. Murray and Renard's

[30] See map prepared by Collet and Lee, *Proc. Royal Soc. of Edinburgh*, vol. XXVI., p. 238, 1906.

[31] Van Hise and Leith, U. S. G. S. Mon., vol. 52, p. 503, 1911.

[32] The thickest continuous section of glauconite-bearing beds recorded occurs in the Cretaceous of New Jersey (Eckel, E. C., "Iron Ores," p. 156, 1914). This is 50 ft. thick, while the Biwabik and Gunflint formations range from 300 to 750 ft. in thickness, with only small amounts of clastic material included.

theory was admittedly tentative and there is as yet no general agreement as to the processes involved in the formation of glauconite, though the surrounding conditions are well known. Glauconite deposits commonly include a considerable amount of clastic material, but mere association does not prove a causal connection. To date it has not been proved that this associated clastic material plays any essential part in the formation of extensive glauconite deposits. In short, the suggestion is that the current theories for the origin of glauconite may be in need of revision in the light of recent information. With these theories open to question, objections (*a*) and (*b*) lose their weight.

As for objection (*c*), it is not necessary to assume an exceptional supply of iron and silica to explain these thick Precambrian formations. Contributions of the same order of magnitude as those being supplied today would be adequate to form thick deposits if deposition were confined to one area for a sufficient length of time, and a simple calculation such as Gruner [33] has made indicates that the time required would not be unreasonable.

The Precambrian is generally considered to have been at least as long as all the succeeding eras combined. Known Precambrian iron formations occurring in sedimentary series are few in number, but relatively of great thickness. On the other hand, iron-rich formations included in sedimentary series from the Cambrian onward are much more numerous, but, on the average, much thinner. Thus the total thickness of distinctly sedimentary iron formations occurring in the Precambrian is not nearly so unusual as is the thickness of such a formation as the Biwabik. It would seem that, during the Precambrian, deposition occurred in a few areas, such as the Lake Superior district, Hudson Bay and Brazil for long periods, whereas later the centers of accumulation shifted frequently, giving a greater number of relatively thin formations. This, at least, is a possible explanation.

That notable quantities of both iron and silica may have been contributed from time to time directly from magmatic sources to Precambrian, as well as to later formations, cannot be denied.

[33] Gruner, John W., *op. cit.*

However, so far as the writer is aware, such an origin has not been proved for any iron-rich formation of great areal extent, occurring as a unit in a sedimentary series, not even for a thin one. Collins and Quirke [34] have published recently convincing evidence to show that the iron in the Michipicoten iron ranges was supplied mainly by hotsprings, but these deposits are not at all comparable in composition, size, or relations with the distinctly sedimentary formations being discussed. To quote the authors:

> Apparently the iron formations were formed by ascending heated mineralized waters at many loci in a land of great volcanic activity. These loci ranged in area from a few yards to seven or eight miles in major horizontal extent and they are to be found throughout the vertical range of the volcanic complex.[34]

There is clear evidence of replacement of the associated volcanics by siderite and pyrite.

IRON AND SILICA IN NATURE.

Solution.—Decomposition of iron-bearing silicates is the chief process by which iron is made available in soluble form. This takes place partly by simple oxidation, but mainly by the action of inorganic and organic acids. Iron may go into true solution or colloidal solution. Soluble salts of iron probably have a transitory existence in river waters unless organic matter is abundant or unless the iron forms part of a complex organic salt.[35] The ultimate product in most instances is hydrated ferric oxide which may form as a gelatinous precipitate directly or may go into colloidal solution. Colloidal solutions may also form by peptization of ferric hydroxide formed by surface decomposition of rock-forming minerals. In ferric hydroxide sols, the disperse phase is positively charged [36] and is susceptible to coagulation by electrolytes that are abundant in nature. Coagulation may, however, be deferred by the presence of certain other colloids which have a protective effect on these sols. Chromic oxide has such a pro-

[34] "Michipicoten Iron Ranges," Can. Geol. Survey Mem. 147, p. 75, 1926.

[35] Harder, E. C., U. S. G. S., Prof. Paper 113, p. 68, 1919.

[36] Boydell, H. C., "The Rôle of Colloidal Solutions in the Formation of Mineral Deposits," *Inst. Min. & Met. Bull.*, no. 243, p. 12, 1924.

tective effect [37] and organic colloids probably act in the same way.[38]

Gruner has recently stressed the part played by organic colloids in the solution of iron and silica and in causing their retention in solution. He found experimentally, that solutions obtained by allowing water to percolate through peat, dissolve all the oxides, the carbonate and most of the silicates of iron, but do not seem to attack pyrite. These solutions are more effective than carbonic acid alone, in that they reduce ferric iron to the ferrous state. By adsorption of the base in solutions of neutral salts, they set free acids that may dissolve iron and silica. Artificial sea water precipitated iron and silica from these peat solutions only partially or not at all. From 2 to 8 parts per million were found to remain in solution in most instances.

The above data indicate that considerable quantities of iron and silica are being carried to the ocean in solution in river water, partly in true solution, but mainly as colloids. That carried in true solutions and unprotected sols is probably precipitated immediately on coming in contact with sea water. Those sols in which the disperse phase is held in solution by virtue of protective agents such as organic colloids, may retain their stability even in contact with sea water for prolonged periods and may be transported for long distances before being coagulated.

Table II. gives figures for iron and silica found in waters from rivers in various parts of the world. Those in which iron is most abundant have been selected.

One would naturally expect that the compositions of river waters would depend to a large extent on the character of the rocks in the areas drained. Palmer [39] has shown that this is the case and has invented an ingenious method by which their characteristics can readily be compared. He has pointed out a relationship between the silica content and the "primary alkalinity," that is, the excess of the alkaline radicals over the strong acid

[37] Bancroft, W. D., "Applied Colloid Chemistry," p. 170, 1921.

[38] Gruner, John W., "Organic Matter and the Origin of the Biwabik Formation," Econ. Geol., vol. 17, p. 445, 1922.

[39] Palmer, Chase, U. S. G. S. Bull. 479.

radicals, probably representing alkaline carbonates, which are readily hydrolyzed. This relationship is found to be independent of climatic zones and the abundance of organic matter.[41]

TABLE II.

IRON AND SILICA IN RIVER WATERS.[40]

(*Parts per Million.*)

River.	$Fe_2O_3 + Al_2O_3$.	Fe_2O_3.	SiO_2.
Plata		4.0	19.1
Amazon	4.8		10.5
Thames	10.9		14.6
Loire		5.0	42.3
Garonne		3.1	40.5
Om		6.3	29.1

Analyses of river waters in general show a similar lack of relationship between the quantity of organic matter present and the amount of iron carried in solution.

Gruner believes that tropical conditions and abundant organic matter are particularly favorable for the removal of large quantities of iron in solution. The analyses listed above, which are selected, and do not at all represent the averages of rivers in the regions from which they are taken, show, however, that certain rivers in temperate zones carry as much or more iron in solution as do the tropical rivers. In most of these instances the total amount of iron contributed to the ocean in any given length of time is much less than that contributed by a large river like the Amazon, but this is merely the result of the present physiographic configuration, which limits the size of the basins that they drain. Conditions have doubtless been reversed many times in the past.

Pohle[42] gives some information regarding the rivers of northern Russia that is interesting in this connection. In these rivers,

[40] Taken from analyses published by Clarke in "The Data of Geochemistry," U. S. G. S. Bull. 770, where references to original publications and names of analysts are given. Percentages have been recalculated to parts per million.

[41] Palmer, Chase, *op. cit.*, pp. 27–28.

[42] Pohle, "Beitrage zur Kenntnis der westibirischen Tiefebene," *Zeitschr. d. Gesellsch. f. Erdkunde z. Berlin*, II., 1919.

especially the Ob, with the appearance of the "Samor" (freeze-up), the water becomes turbid. The suspended particles consist of precipitated iron hydroxide, which is called "Rust." The only analysis of water from this river system that the writer has been able to obtain is that from the Om (see table above), a tributary of the Irdysch, which in turn flows into the Ob. Iron and silica are both conspicuously high.

Though a moderate amount of organic matter is necessary to insure the retention of considerable amounts of iron in solution, a superabundance does not seem to be necessary. The requisite conditions are found in regions with moist climates and moderate or low relief, in both temperate and tropical zones.

Precipitation.—What becomes of this great amount of iron and silica being carried to the sea in solution after it reaches the ocean basins? In general, deposition of materials from solution tends toward concentration of those substances that react similarly under a given set of conditions. Usually only a few substances are deposited simultaneously, and the purity of the deposit depends largely on the quantity of admixed clastic sediment. Iron and silica are not necessarily deposited in the same localities under all conditions, but under the conditions that existed in the Lake Superior region in the Animikie, they undoubtedly were, in large part.

Turning to modern sediments, we find that the only ones with a high concentration of iron are glauconitic and this suggests that a considerable proportion of the iron carried to the sea in solution eventually finds its way into glauconite.

A study of the following data (Table III.) indicates that this is true.

Comparing first the figures for the average igneous rock with the ones for the average sedimentary rock, it is seen that, as would be expected, in the latter there is a great increase in the ferric iron at the expense of the ferrous. In addition, however, there is a reduction of nearly 25 per cent. in the total iron content. Since the analysis given for sedimentary rocks includes only shallow water facies, *i.e.*, limestones, shales and sandstones, it is obvious

that this deficiency in iron represents iron carried to the greater depths of the ocean in solution. The figure given cannot, of course, be taken as an absolute measure of the amount of iron removed in solution, but that considerable amounts are so removed is surely indicated, bearing out the conclusions drawn from other data already submitted.

TABLE III.

AVERAGE ANALYSES OF SEDIMENTS AND IGNEOUS ROCKS.

	1. Red Clays.	2. Blue Muds (48), Green Muds (4).	3. Limestones, Shales, Sandstones.	4. Igneous Rocks.
Fe_2O_3	8.66	5.07	3.37	3.08
FeO	0.84	2.30	2.00	3.80
Fe	6.71	5.34	3.77	5.01
SiO_2	54.48	57.05	58.53	59.12

1. Composite of 51 samples of "red clay." Analysis by G. Steiger.[43]
2. Composite of 52 samples of "terrigenous clays." Analysis by G. Steiger.[43]
3. Average composition of sedimentary rocks, Clarke and Washington, U. S. G. S. Prof. Paper 127, p. 29.
4. Average igneous rock. Clarke and Washington, *op. cit.*, p. 12.

The amount of iron retained in solution in sea water is extremely small, therefore practically all of this dissolved iron must be deposited eventually somewhere in the deeper parts of the ocean. Clarke calculated that the annual chemical or biotic sediments contain 75,213,000 metric tons of $(Fe, Al)_2O_3$.[44]

The figures for the commonest deep sea sediments, which are the best available, show that the red clays are conspicuously higher in iron than the average igneous rock, while the blue and green muds are only slightly higher. According to Sir John Murray,[45] red clays consist mainly of materials derived from the decomposi-

[43] Given by F. W. Clarke, "Data of Geochemistry," U. S. G. S. Bull. 770, p. 518, 1924. Of these he says: "The samples analyzed were composites of many individual specimens, brought together from all the great oceans and collected partly by the *Challenger* and partly by other expeditions."

[44] Clarke, F. W., "Some Geochemical Statistics," *Proc. Am. Phil. Soc.*, vol. LI., p. 230, 1912.

[45] "On the Distribution of Volcanic Debris over the Floor of the Ocean," *Proc. Roy. Soc. Edinburgh*, vol. IX., pp. 247–261.

tion of aluminous silicates and rocks spread over the ocean basins by subaërial and submarine eruptions. Renard [46] laid more stress on submarine eruptions than admitted by Murray. Both think that colloidal clayey material coming from the land may play some part in the formation of these deposits. Submarine eruptions are dominantly basic. The figures for the iron content of red clays given in the above table agree fairly well with those for basic igneous rocks such as basalts or andesites and therefore no significant contributions from the land are indicated.

The blue muds are deposits most frequently met with in the deeper waters surrounding the land, and in all enclosed seas. The materials composing them are derived principally from the disintegration of continental land and are complex in character.[47] Thus, with continental sediments again dominant, the iron, as shown by the average analysis, approaches more nearly that of the average igneous rock, but is still slightly higher.

With the exception of glauconite deposits, the other deep sea sediments have a smaller average iron content than those already discussed. Glauconite deposits are widespread, occurring along the coasts of all the continents and covering an aggregate area of approximately 850,000 square miles. Andrée thinks that this original figure, given by Murray and Renard, must be increased in the light of more recent data. The conclusion that a large part of the iron carried to the sea in solution finds its way into these deposits seems to be inescapable.

Considering the figures for silica, the average content of the red clays is in agreement with derivation from debris of basic volcanic eruptions. The deficiency in the terrigenous sediments is readily accounted for by concentration of silica in the areas of diatomaceous and radiolarian ooze. In part it may be deposited along with the iron in glauconite deposits.

ORIGIN OF GLAUCONITE.

Glauconite was early shown to be forming in modern seas and the literature dealing with its origin is quite extensive. Andrée [48]

[46] "Deep Sea Deposits," p. 190.

[47] *Ibid.*, p. 229.

[48] Andrée, K., "Geologie des Meeresbodens," pp. 241–250, 1920.

and Hummel [49] give references to all the more important works.

The well-established facts concerning the formation of glauconite deposits in modern seas may be summarized as follows:

1. Glauconite is an amorphous or microcrystalline mineral of uncertain composition and the materials composing it have probably passed through the colloidal state.

2. It is found most commonly as small grains irregular in outward form and also as casts of foraminifera and other organisms.

3. It has been observed to form in some instances by alteration of brown or gray casts or of mineral grains.

4. It forms most abundantly at about the lower limits of wave, tidal and current action, that is, at depths of from 200 to 300 fathoms, along the coasts of continental landmasses, and in areas of slow sedimentation.[50]

5. Areas in which cold and warm ocean currents meet and mingle seem to be particularly favorable.[51]

6. It commonly forms at temperatures between 3° and 15° C.[51]

7. Almost all the common rock-forming minerals are locally represented amongst its associates, the most common being feldspar and quartz. The proportion of these fragmental particles is quite variable.

Most writers have followed Murray and Renard in accounting for the formation of glauconite by submarine decomposition of terrigenous sediments *in situ*, the iron being derived from the iron-bearing minerals in the original sediments. The main arguments supporting this conclusion seem to be (1) the difficulty of accounting for the transportation of iron-rich substances to places of modern glauconite deposition in any other way, (2) the commonly observed association of detrital material with glauconite casts and (3) the observed alteration of detrital mineral particles to a greenish mineral resembling glauconite.

Recent information indicates that ferric hydroxide sols may persist for a considerable period of time after being brought into

[49] Hummel, K., "Die Entstehung eisenreicher Gesteine durch Halmyrolyse," *Geol. Rundschau*, B. 13, p. 49, 1922.

[50] Murray and Renard, "Deep Sea Deposits."

[51] Hummel, K., *op. cit.*

contact with sea water, when a suitable protective agent is present. The mineral formed when deposition occurs must vary with the physical and chemical environment.

The formation of glauconite casts in shells of organisms that happened to be present would take place by infiltration of chemically precipitated glauconite just as readily as would the original casts of aluminous silicates assumed on the above hypothesis. Wherever fine detrital muds accompanied such chemical precipitates, similar casts of these materials would form. That glauconite or other iron-rich silicates might result from reaction between the iron-rich substances brought in in solution and some of the detrital minerals is admitted. The writer has observed evidence of similar alteration in pyroclastic particles from some of the slaty beds of the Gunflint formation. The transitions from gray to brown to green casts observed by Collet and Lee [52] are probably due to such reactions.

Leith in 1903 [53] pointed out one of the chief difficulties involved in Murray and Renard's theory, showing that to obtain a sediment averaging 25 per cent. iron, as do the greenalite rocks of the Mesabi district, normal sediments several times the present thickness of iron-rich sediments must originally have been present to have supplied the iron. Caspari [54] calculated that from a normal clay with 5 to 10 per cent. Fe_2O_3, about 10 to 15 per cent. of Al_2O_3 and a somewhat greater quantity of silica must be removed to leave a glauconite deposit with 20 to 30 per cent. Fe_2O_3. This means a total removal of about 1/3 of the original mass of sediment. Hummel finds a vehicle for such wholesale removal in peptization of these substances and transportation to other areas of the ocean bottom by ocean currents. The assumption that great quantities of terrestrial sediments are transported in suspension, deposited for a brief period during which decomposition and rearrangement of the components take place, and then one third of the original bulk carried off in colloidal solutions seems a little

[52] *Proc. Royal Society of Edinburgh*, 1906, p. ?.

[53] Leith, C. K., U. S. G. S. Mon. 43, 1903.

[54] Caspari, W. A., "Contributions to the Chemistry of Submarine Glauconite," *Proc. Royal Society of Edinburgh*, 30, pp. 364–373, 1910.

strained. He abandons the hypothesis that iron has been transported to the sea in solution because of the extremely small content of iron found in solution in sea water.

The data assembled in the preceding pages indicate strongly that the iron in modern glauconite deposits is mainly derived from the continents and transported to areas of localized glauconite deposition in colloidal solution. Until our knowledge of colloid chemistry and the bottom conditions in modern seas is extended further, no certain explanation of the precipitation can be given. It may have been effected by the simple removal of a protective agent by reaction with some other substance, or by oxidation, or it may have occurred by reaction between a ferric hydroxide sol and fine suspended material accompanying it or encountered by it. It seems clear that some glauconite has formed by reaction between iron salts and fine clastic sediments. Locally temperature changes or organisms may have played some part in the precipitation.

OTHER SEDIMENTARY IRON DEPOSITS.

That most of the extensive oölitic hematite ores are primary in origin may be accepted as proven by the work of Smyth and others.[55]

Hummel, in the very suggestive paper already cited, has pointed out the paleoclimatic significance of glauconite deposits and, from data made available by the deep sea expeditions, has indicated the probable changes in conditions of formation necessary for the production of the leptochlorites and oölitic iron ores.

At Challenger station 185b (Torres Strait), a substance reddish brown in color, but otherwise resembling glauconite was brought up. The analysis of this material shows, however, that the Fe_2O_3 content is significantly higher and K_2O and SiO_2 much lower. This is the only analysis given of a greenalite-like substance from a warm water region, the bottom temperature here being 17.5 degrees C. as against 3 to 15 degrees for glauconite

[55] Smyth, C. H., Jr., "The Clinton Type of Iron-Ore Deposit," in "Types of Ore Deposits," edited by H. Foster Bain, 1911, pp. 33–52. Hayes, A. O., "Wabana Iron Ore of Newfoundland," Can. Geol. Survey, Mem. 78, 1915.

deposits. The leptochlorites resemble glauconite in being variable in composition, and seldom crystalline. In composition they differ from glauconite in having a higher total iron content, a greater proportion of Fe″ to Fe‴ and less SiO_2 and K_2O. The Torres Strait mineral varies in this general direction though the iron is mostly ferric, and Hummel therefore concludes that a higher temperature is probably one of the conditions that favors the formation of leptochlorites instead of glauconite. Leptochlorites are common constituents of iron oölites and a higher temperature would probably also favor the formation of such rocks.

Sea water is a very complex chemical reagent. Which of the above minerals will form under a given set of conditions will depend on the temperature, pressure and the compositions of the sea water and solids present. Small changes of pressure have but little effect on the formation of such compounds, so that the temperature and composition of the system are the controlling factors and both doubtless play an important part.

QUANTITATIVE CONSIDERATIONS.

According to the figures given by Clark (see Table II.), the shallow water terrigenous sediments are deficient in iron as compared with the average igneous rock to an amount equal to 24 per cent. of the iron or about 1.2 per cent. of the whole. These are minimum figures if the analyses are assumed to be correct averages, for considerable quantities of other constituents such as Na_2O, K_2O, SiO_2 must have been removed in solution, thus increasing the relative proportion of the iron left.

The average iron content of the Biwabik and Gunflint formations may be taken as approximately 25 per cent. This figure also expresses approximately the average iron content of all the original phases of the iron-bearing formations in the Lake Superior district.[56] Assuming that the conditions in the Animikie were approximately the same as at present, and that the 1.2 per cent. iron deficiency of the sandstones, shales and limestones

[56] Mon. U. S. G. S., p. 462.

represents iron carried in solution and contributed to iron-rich sediments, the other materials making up the sediment being likewise of land derivation, a sediment containing 25 per cent. Fe must include about 1/20th of the original average rock. That is, for every unit of iron formation, 19 or 20 units of other sediments were formed in the ocean basins or on the continents. If we assume that the adjacent lands were underlain by rocks dominantly basic, averaging say 8 or 9 per cent. Fe and that, as above, about one fourth of this was contributed to iron-rich sediments averaging 25 per cent. Fe, the total mass of other terrigenous sediments formed at the same time must have amounted to about 10 times the mass of the iron formations. Furthermore, if a greater proportion of the iron in the original rocks was contributed to iron-rich sediments than has been assumed, the relative proportion of these to the others formed at the same time would be further increased. If less, the ratio would decrease. The above figures give an approximate idea of the maximum proportion of iron formation which may form from terrigenous materials under the most favorable circumstances. Stratigraphic data show us that the average proportion must be very much less. This is probably due in part to the deposition of part of the dissolved iron in more disseminated form in the green muds, red clays and other deep sea deposits, in part perhaps also to the inaccuracy of the averages on which the above figures are based.

Whatever the proportion of iron-rich to other sediments, the iron formations must grade at their margins into other types of chemical or clastic sediments. Such gradations are recognized at the southwest end of the Mesabi range. The other products resulting from the breaking down of the original rocks of the land were for the most part deposited in other parts of the basin floor, probably covering a large area. Most of these beds have undoubtedly been destroyed by erosion. We can recognize contemporaneous sediments to the southwest and northeast, by actually tracing the beds through. Elsewhere, even if remnants were preserved, it would be impossible to make exact correlations because of the absence of fossils.

In the Gunflint district there is distinct evidence of peneplanation following the Keweenawan. The Logan sills, that cap the saw-tooth ridges to the southeast of the granitic upland have been deeply truncated, so that coarse grained phases oftentimes are found at the crests of the ridges. The summits of these are accordant and stand at about the same elevation as the partially dissected granitic plateau to the northwest. It seems quite clear that the Animikie sediments and the sills extended much farther to the northwest than we find them at present. It is generally assumed that the old shoreline lay to the northwest or north, and it is possible that the iron formation graded out in this direction into sediments of more usual types.

As to the nature of the rocks that formed the surface of the land to the north and northwest, there is no definite information. At present this consists of great masses of granite and gneisses, with here and there recognizable remnants of ancient sediments and volcanics. If we project the present dip of the Animikie sediments toward the northwest, it appears immediately that a tremendous volume of rock must have been removed from this area since the deposition of the iron formation. The land that supplied the materials for the iron formation no doubt presented a markedly different appearance from that of its modern equivalent. It seems probable that pre-Animikie sediments and volcanics were much more in evidence at the surface than they are at present.

GENERAL SUMMARY.

1. Recent chemical data indicate that much of the iron and perhaps some of the silica in modern glauconite deposits have been carried from the continents as colloids stabilized by protective agents, such as colloidal organic matter.

2. The distribution of iron-rich sediments in time and space suggests that those occurring as extensive stratigraphic units interbedded with normal sediments are normal by-products of the processes that formed sandstones, shales and limestones from the rocks of the continents. The manner of formation of each is believed to be, in part at least, similar to that of modern glau-

conite beds. Variations in the temperature and composition of the sea water or in the associated clastic particles must have caused different iron minerals to be deposited at different times, or in different areas at the same time. Enlightenment as to the conditions favoring the formation of each of the various types of iron-rich sediments can only come through close studies of the bottom conditions in the modern oceans. Important suggestions have come from information now available, but this information is still much too scant to permit any definite conclusions.

3. If the views expressed above regarding the origin of glauconite are found to be correct, objections to a glauconite-like origin for the Biwabik-Gunflint formation are much less formidable than formerly believed.

4. In the nature of the case, one cannot prove that great quantities of iron and silica were not contributed directly to the oceans by magmas in the Precambrian, but such an assumption seems less necessary than it did a few years ago. That considerable quantities of both iron and silica were at times so contributed is perhaps true, but it is the writer's belief that too much importance has been assigned to this process.

CONCLUSIONS REGARDING THE ORIGIN OF THE GUNFLINT FORMATION.

During the Animikie period, continental weathering proceeded much as it does today. A landmass of low or moderate relief in a temperate or tropical climate was subjected to deep decay. Amongst other substances, iron and silica were carried to the sea by rivers, principally as colloids stabilized by protective agents. The usual clastic sediments were deposited near the river mouths, but the sols retained their stability long enough to be carried relatively long distances by off-shore currents to areas of shallow or moderate depth, in which fine, suspended particles were deposited rarely and only during brief periods. These conditions maintained for a much longer time than in most other periods in the earth's history, resulted in the formation of an exceptionally thick series of sediments consisting almost wholly of iron compounds and silica.

Volcanism occurred, particularly during the latter half of the iron formation period. Some silica and iron may have been contributed directly by magmatic springs or by submarine lava flows, but the total quantity supplied in this way is believed to be relatively small.

Organisms may have played a part in the precipitation, but they were probably not essential and the main reactions involved are believed to have been entirely independent of them. Possibly the mingling of solutions from different sources was one of the principal factors in bringing about these reactions, the nature of which can only be surmised. Ordinarily, gelatinous silica formed the bulk of the precipitate, and variable proportions of iron compounds were adsorbed by or admixed with it. The bulk composition undoubtedly varied a good deal with changes in the surrounding conditions and in the proportions of the various constituents brought in. Chemical rearrangements may have occurred during or shortly after the precipitation. At any rate, the final product consisted sometimes of hydrated ferrous silicate and silica, sometimes of hydrated ferric oxide and silica, and, more rarely, of all three of these substances. Ferrous carbonate developed in considerable abundance locally, probably by reaction between ferric hydroxide or greenalite and organic matter. Calcium carbonate was also precipitated locally, and reaction of part of this with ferrous salts may have accounted for some of the ferrous carbonate. Locally, and for brief periods, these substances formed a large part of the precipitate.

Like most amorphous precipitates, the hydrated ferrous silicate and hydrated ferric oxide formed minute globules, which sometimes united to form larger aggregates of approximately the same form. Under certain conditions, this segregation into droplets was imperfectly attained and the above substances remained as more or less irregular shreds or bands in the gelatinous silica. The granules had obviously attained much their present size and form and the silica had been fairly completely dehydrated at an early stage, much before the crystallization of the main mass of the silica which filled the interstices between the granules, for the latter is commonly observed filling contraction cracks in the granules.

Where carbonates were precipitated, they also tended to form spherical segregations, which sometimes grew to much larger sizes than the ordinary granules. Much of this segregation probably took place during diagenesis, by diffusion in the incompletely dehydrated, uncrystallized or only partially crystallized silica of the groundmass, for many of the larger carbonate segregations inclose greenalite granules toward their margins and, in some instances, the cryptocrystalline silica of these granules has been partially or wholly replaced by the carbonate.

In general, the conditions that favored the formation of the hematite-chert granules were unfavorable for the formation of greenalite granules, for each type is ordinarily confined to definite beds persistent over large areas. Intermediate conditions resulted locally in transition rocks, containing both types of granules, but such rocks are relatively rare.

Twice during the deposition of the formation, algæ(?) flourished in the areas at present occupied by the iron formation outcrop, giving a peculiar arrangement to the chert, greenalite and hematite deposited at those times. The presence of associated intraformational conglomerates indicates that shallow water conditions prevailed at these times. In the Gunflint formation a thin pisolitic bed and locally oölite, made up of granules with added rhythmically banded chert, greenalite and hematite, formed under similar conditions.

Some of the beds show only very slight evidence of alteration since they originally solidified to form hard rocks. In many, small amounts of finely crystallized amphiboles and some magnetite have been developed from the original minerals. This may be attributed to higher temperatures and pressures developed as a result of loading by superimposed sediments. Where more extensive recrystallization has occurred, it is always directly attributable to contact metamorphism by the sills that were thrust in along the bedding planes toward the end of the Keweenawan period. Locally this has completely obliterated the original textures. Only a small amount of surface decomposition has occurred in the portions of the formation now visible.

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REPLACEMENT *VS.* IMPREGNATION IN PETRIFIED WOOD.

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Although there are many references in the literature to petrified wood,[1] the actual method by which the vegetable tissue has been fossilized is not always clear, the process being variously referred to as petrification, infiltration, or replacement, all of which leave the reader in some doubt.

Many minerals have also been referred to as petrifying agents. The commonest of these is some form of silica, including quartz, opal, chalcedony, carnelian, onyx, amethyst, jasper, or agate. Calcite, aragonite, pyrite, and marcasite are also quoted fairly often. Others listed are dolomite, by Adams,[2] cinnabar, barite, fluorite, sulphur, malachite, gypsum, phosphorite, hematite, limonite, siderite, galena, chalcopyrite, chalcocite, halloysite, and talc, by Blum;[3] chlorite, pyrophyllite, and phosphate by Grabau,[4] bornite, covellite, melaconite, hematite, pyrite, chalcocite, and chalcopyrite by Rogers.[5] Other writers also list a number.[6]

Problems Involved.—In considering the process of petrifaction, two problems present themselves, viz: (1) What was the condition of the vegetable tissue at the time it was permeated by mineral solutions, and (2) was the process one of actual replacement, or infiltration of mineral matter into the spaces between the cellular tissue, or both.

[1] See particularly a bibliography by F. H. Knowlton in paper on "Fossil Wood and Lignite of the Potomac Formation," U. S. Geol. Surv., Bull. 56, pp. 11–67, 1889.

[2] *Jour. Geol.*, XXVIII., p. 356, 1920.

[3] "Pseudomorphosen des Mineralreichs," Nachträge, 1, 2, 3, 4.

[4] "Principles of Stratigraphy," p. 1080, 1913.

[5] Econ. Geol., vol. 11, p. 366, 1916.

[6] Berry, E. W., "Tree Ancestors," p. 10, 1923; Emmons, S. F., U. S. Geol. Surv., Bull. 260, p. 221, 1905; Hickling, G., *Geol. Mag.*, VI., vol. 3, p. 516, 1916.

Condition of Vegetable Matter.—The opinions of different writers regarding the condition of the vegetable tissue at the time the minerals were deposited in it varies somewhat, but four main types of view are expressed.

Göppert (cited by Solms-Laubach),[7] after dissolving the mineral matter out of fossil wood, obtained cellulose reactions from the vegetable matter left. Similar conditions are reported by Walton,[8] Stocks,[9] and Grabau.[10]

Scott [11] and Fettke [12] note that the vegetable tissues remain, but in a chemically altered form.

Others, as Adams [13] and Greenland,[14] refer to the preservation of the cell walls as organic rings.

Finally, another group, including Schrader,[15] Lesquereux,[16] Dawson,[17] and Rogers [18] state or intimate that the woody tissue was altered to coaly matter before the minerals were introduced.

Replacement versus Infiltration.—It appears that in most specimens of petrified wood examined by the writer, the vegetable structure may show megascopically, or if not, it usually does when examined in thin section by ordinary light. This refers, however, only to silicified and calcified material.

The fact that the woody material appears, in hand specimens, to be composed entirely of the later mineral seems to indicate, on first thought, that the vegetable tissue has been entirely replaced.

There are, however, four possibilities, as follows: (1) The mineralizing solution may have deposited mineral matter by true replacement of all the plant tissue, completely obliterating the vegetable structure; (2) infiltration may have occurred, leaving

[7] Fossil Botany, 1891.
[8] *Ann. Botany,* XXXVII., p. 379, 1923.
[9] *Geol. Jour.,* LVIII., p. 46, 1902.
[10] "Principles of Stratigraphy," p. 1080, 1913.
[11] "Studies in Fossil Botany," pp. 9–14, 1909.
[12] *Amer. Mineralogist,* X., No. 5, 1926.
[13] *Jour. Geol.,* XXVIII., p. 356, 1920.
[14] Econ. Geol., vol. 13, p. 116, 1918.
[15] U. S. Geol. Surv., Prof. Paper 68, p. 141, 1910.
[16] Geol. Surv., Ill., IV., p. 483, 1870.
[17] *Proc. Amer. Assoc. Adv. Sci.,* X., p. 174, 1856.
[18] Econ. Geol., vol. 11, p. 366, 1916.

the entire cell walls, or remnants of the cell wall material marking the outlines of the original cells; (3) there may have been infiltration, followed by replacement of the cell walls; or (4) infiltration into the cell cavities may have been followed by decay of the cell walls and another period of infiltration. In the last two cases, the specimen might be composed entirely of mineral matter, but the cell structure may be preserved, due to differences in the texture or the appearance of the materials of the two periods of deposition.

If complete replacement has occurred, as in processes (1) or (4), mentioned above, then on dissolving the deposited mineral, no plant tissue should be left.

If, however, the process of mineralization involved simply a filling of the cells and intercellular spaces by deposited mineral matter, then, on treating the specimen with the proper solvent, the plant tissue should remain behind in a more or less complete state of preservation. This might occur whether the original cellulose remained, or had been altered, say to coaly material, or even partly decomposed.

Previous Theories.—In looking over the literature, one finds that both the replacement and the infiltration theories, or even a combination of these have been stressed by different writers, without always giving evidence, experimental or otherwise.

Among those who have suggested complete replacement are: Boyd-Dawkins,[19] Berry,[20] Grabau,[21] Miller (quoted by Knowlton [22]), Lyell,[23] Lyons,[24] and Merrill.[25]

David White [26] also subscribes to the molecular replacement theory, and uses the term "histometabasis" for causes of fossilization" in which an entire exchange of the original substance for

[19] *Geol. Mag.*, VI., III., p. 518, 1916.
[20] Tree Ancestors, pp. 10–13, 1923.
[21] *Buffalo Soc. Nat. Sci.*, Bull. VI., p. 12, 1898.
[22] *Am. Forestry*, XIX., p. 207, 1913.
[23] Elements of Geology, p. 38, 1865.
[24] *Geol. Jour.*, L., p. 545, 1894.
[25] *Am. Mus. Jour.*, XIII., p. 311, 1913.
[26] Rept. U. S. Nat. Mus., p. 264, 1892.

another has occurred in such a way as to retain or reproduce the minute, or even the microscopic texture of the original."

Stopes [27] speaks of the "replacement" of the cell walls in which the substances "completely replace and petrify each individual cell of the plants in them" (referring to coal balls) using the term "petrifaction" for this process. In another place, however, she also recognizes infiltration, as mentioned later.

The infiltration theory, which assumes that the solutions entering the tissues have deposited their dissolved mineral matter in all the cracks, and even the microscopic openings in, and between the cells, as well as in the spaces left by the disappearance of the cell fluids, thus preserving the form and structure of the tissue, has been strongly urged, or intimated, by another large group of observers. It was evidently meant by Webster [28] as early as 1826.

Stokes seems to have noted it in specimens of calcified wood from a Roman aqueduct,[29] and Seward [30] also refers to it.

Wherry has described another interesting case in which he speaks of clear calcite grains surrounded by a black rim of evidently organic matter crowded out by the growing crystal, which seems to indicate deposition in cavities rather than replacement. He furthermore refers to the openings in the wood filled with quartz.[31]

Stopes and Wheeler [32] also definitely describe filling, although noting that the replacement theory is widespread.

Among those who recognize the existence of both processes are Grabau,[33] Jeffrey,[34] Nicholson,[35] Pelourde,[36] Lesquereux,[37] and others.

[27] "Ancient Plants," London, 1910.
[28] *Trans. Geol. Soc.*, Ser. II., vol. II., p. 42, 1826.
[29] *Trans. Geol. Soc.*, Ser. II., vol. V., p. 207, 1840.
[30] "Links with the Past in the Plant World," p. 56, Cambridge, 1911.
[31] *Proc. U. S. Nat. Mus.*, LIII., p. 227, 1917.
[32] Constitution of Coal, Dept. of Sci. and Ind. Res., 1918.
[33] "Principles of Stratigraphy," p. 1080, 1913.
[34] "Science Conspectus," IV., No. 3, 1916.
[35] "Manual of Paleontology," 1872.
[36] "Paléontologie Végétale," p. 19, 1914.
[37] Geol. Surv. Ill., IV., p. 483, 1870.

Condition of the Wood at the Time of Petrifaction.—It seems very probable, both from the literature, and from the writer's experiments, that the wood, at the time of fossilization, may have been either fairly fresh or partly decayed. Byers [38] asserts that the different forms of silica in the petrified woods of Arizona are due to the state of preservation of the log at the time of petrifaction, and to the stage of compactness prior to exposure on the surface by erosion. This brings up the thought as to whether silicification, for example, took place when the wood was entombed in the rock, or whether it went on when the material was brought into the zone of weathering, by erosion, since it is recognized that silicification is sometimes a surface process. It is possible that petrifaction might also take place in unconsolidated rocks.[39]

Experiments in Fossilization.—Stocks [40] tried applying iron salts and sodium carbonate alternately to a specimen of wood. After a time, the wood become harder, and was penetrated by ferric hydrate. In another set of experiments in which calcium and sodium carbonate were alternately applied to wood, it was found that the cells became filled with crystalline calcite, and that nodules of the same material formed on the exterior of the specimen.

Experiments by the Writer.—The experiments made by the writer were carried out for the purpose of determining whether the petrifaction of wood was chiefly a process of replacement or infiltration.

The specimens used were all, with one exception, so-called silicified woods, the exception being a piece of calcified material from Kansas. In most of the specimens, plant tissue was visible megascopically, but in some, the material was hard, silicified, and showed no such structure visible to the naked eye.

The silicified pieces, after being sectioned, were examined under the microscope to determine the presence of visible cellular tissue, and the sections were then treated with hydrofluoric acid and

[38] *Sci. Amer.*, XCII., p. 388, 1905.
[39] Diller, U. S. Geol. Surv., Bull. 150, p. 113, 1898.
[40] *Geol. Jour.*, LVIII., p. 46, 1902.

alcohol, in the proportion of one third of the former to two thirds of the latter. The alcohol serves the double purpose of diluting the acid, and also hardening the plant tissue. After this treatment, the section was again examined to see if any plant tissue remained.

Another method of treatment was to remove the silica from fragments of the fossil wood with hydrofluoric acid and alcohol, and then imbed the pieces in celloidon, following the method used with fresh plant tissue. They could then be sectioned with a microtome. The process did not prove wholly satisfactory, due to the fragility of the desilicified plant tissue.

It may be of interest to note that one silicified specimen showing cell structure was treated with cold concentrated sulphuric acid for four months, which resulted in the disappearance of most of the plant tissue, leaving nothing but the silica behind. This seemed to indicate that vegetable matter was still present in the specimen after silicification.

Of some 25 sections examined, a few may be selected as typical of several processes.

Complete Replacement.—As illustrative of this process reference can be made to a specimen labeled Alder wood, locality unknown. It is mottled in color, ranging from cream white to fairly dark brown, has a hardness of 7, very dense texture, waxy lustre and conchoidal fracture. The woody structure is quite clear megascopically.

Under the microscope, the woody structure (Fig. 1) is also quite evident, although individual cells are somewhat imperfect in appearance, and appear to be elongated in a direction at right angles to the medullary rays.

The mineral matter appears to be entirely composed of noncrystalline silica.

Pieces of the specimen treated for a few days in a mixture of ⅓ hydrofluoric acid and ⅔ alcohol, were entirely dissolved and not a trace of vegetable tissue was left, the only residue being some very fine grains of undeterminable material.

Another specimen (No. 17) from Albuquerque, N. Mex.,

showed in the hand specimen a series of rings, about ¼ inch apart, and many fine radiating lines at right angles to these.

FIG. 1. Transverse section of silicified wood, showing cell structure. Locality unknown.

The cell structure shows up very well in the thin section, but there is a little coloring which might be caused by organic matter, the boundaries of the cells being apparently of silica, which is slightly darker than that filling the cell spaces. The silica is all amorphous.

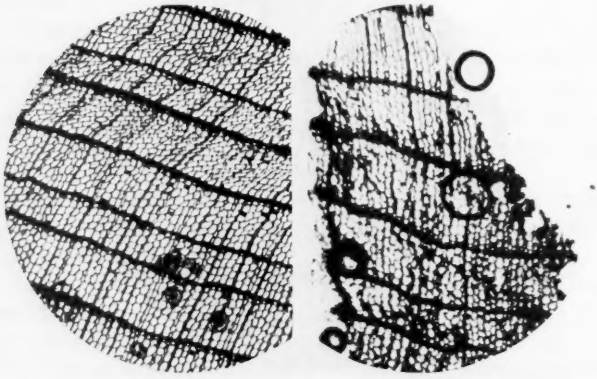
After removal of the silica, no evidence of cell structure was left, so that this also appears to represent a case of complete replacement.

Infiltration.—As an example of this we give illustrations of a specimen from Yellowstone Park (Figs. 2 and 3).

Megascopically this piece shows little evidence of organic structure unless very closely examined. It is nearly black, has a hardness of about 7, microscopic texture, and conchoidal fracture.

A thin section under the microscope (Fig. 2) shows the cellular structure beautifully preserved, the cells being filled with

crystalline quartz. The cells appear to be outlined by dark-colored organic matter. In the cell filling there also appear to be specks of organic material, which have apparently broken off from the cell walls.



2 3

FIG. 2 (left). Transverse section of silicified wood. Showing cell structure.

FIG. 3 (right). Same, after removal of the silica. Yellowstone Park. ×25.

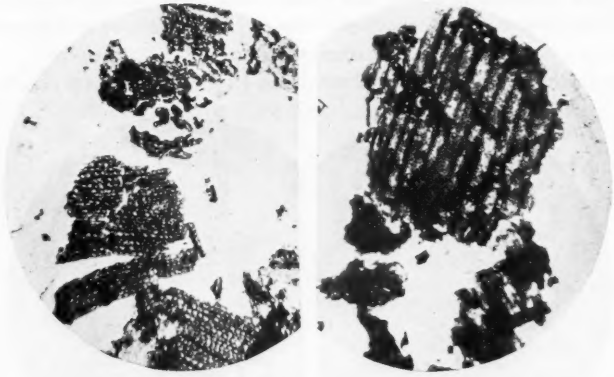
After the material had been treated for 13 days with hydrofluoric acid and alcohol, it was found that the silica was all gone, but the cell tissue remained as well preserved as in the original (Fig. 3).

It seemed quite evident therefore that there was little replacement, but that the spaces in the cell tissue had been filled by the deposition of silica.

Another interesting specimen was a piece of a calcified trunk about 2 inches in diameter, from the Benton formation of Kansas. It had all the appearance of fossilized wood, and was grayish-brown in color. Wherever a drop of hydrochloric acid was placed on the specimen it effervesced violently.

In the hand specimen the knots, annual rings, etc. are plainly seen. Cavities and cracks are filled with calcite.

A thin section (Fig. 4), shows the cell structure well preserved, and the cells filled with calcite. When examined by polarized



4 5

FIG. 4 (left). Transverse section of calcified wood from Benton Formation, Kansas. × 25.

FIG. 5 (right). Splinter from same after removal of calcium carbonate. Note woody structure as in longitudinal section.

light it is found that the individual calcite grains, judging from their optical behavior seem to occupy the area of a number of cells.[41]

The woody matter had possibly decayed somewhat, before the infiltration of the calcite started, because when treated with hydrochloric acid, even slight effervescence caused its disintegration. By using great care in the treatment it was possible to remove all the lime carbonate from a small splinter leaving the cell tissue behind (Fig. 5), thus indicating again a case of infiltration rather than replacement.

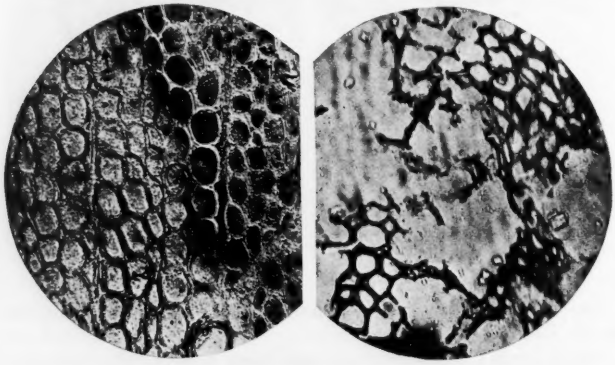
Combined Infiltration and Replacement.—There appear also to be cases where both infiltration and replacement have been active.

[41] Greenland, ECON. GEOL., vol. 13, p. 116, 1918.

or else it is possible that infiltration may have taken place first, and that this was followed by replacement of the plant tissue.

Such an example appears to be shown in Fig. 6. This is a section of a piece of silicified wood from an unknown locality. The hand specimen is dense, and breaks with a conchoidal fracture. It is colored various shades of brown, red, and yellow, and shows little evidence of woody texture megascopically.

In the thin section the plant tissue (Fig. 6) shows up clearly



6 7

FIG. 6 (left). Transverse section of silicified wood. (× 122.) Locality unknown. Note the gradation in replacement: (*a*) organic cell walls remain; (*b*) cells outlined by specks of organic matter; (*c*) no organic matter-cells entirely replaced.

FIG. 7 (right). Same after removal of silica. Note that only portions of the cell walls remain.

and is filled with crystalline silica, the individual grains of the latter occasionally spreading beyond the boundaries of a single cell. The cells appear in some cases to be outlined by lighter colored silica, and in other cases by light and dark colored specks of unidentifiable material. At times the original organic matter of the cell wall appears to remain.

This specimen (Fig. 7) treated with hydrofluoric acid and alcohol for two weeks, showed perfect preservation of the cell

structure in places, but in others it was entirely gone, as though there had been complete replacement in spots.

Conclusions.—After examining a number of sections of which those described above may be regarded as types, it seems that the following cases may occur:

1. Infiltration of mineral matter into the cell cavities and intercellular spaces, with the vegetable tissue preserved.
2. Complete replacement of the plant tissue, but this may be due to the spaces being filled first, and later the tissue being replaced.
3. Complete replacement of portions of the mass, and filling only of cavities in the other parts.

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EDITORIAL

THE PIPE FORM OF ORE DEPOSIT.

BARELY mentioned in even moderately up-to-date works on ore-deposits, mineral pipes have in recent times come into their own. Hardly a year passes but some important new deposit of this type is described, and the pipes are as diverse in nature and origin as they are numerous. That they should have received so little attention in the past is due to our science having been built up rather laboriously on strictly objective lines in areas where the mineral vein is all important. Had a general, or even a strictly morphological classification based on deductive reasoning been attempted, the existence of such pipes could with certainty have been predicted. Ore geology, however, still awaits its Mendeléeff.

The Union of South Africa is *par excellence* the land of pipe deposits. Apart from the volcanic diamond-bearing kimberlite pipes, with which we are not here concerned, there are platinum, tin, tungsten, molybdenum and zinc pipes. Among them are included the richest occurrences in the Union of each of these metals. Genetically the pipes fall into five classes, all of which appear to be represented in other parts of the world. They are:

1. Pipe-shaped segregations in igneous rocks. Here belong the occurrences of platinum-bearing hortonolite-dunite in the norite zone of the Bushveld Igneous Complex from which the bulk of the present South African platinum output is being obtained.

2. Pegmatite pipes in the interiors of which there have developed partly by replacement and partly by cavity-filling minerals such as cassiterite, scheelite, molybdenite, arsenopyrite and bismuthinite.

3. Pipes formed in granite independently of fissures by pneu-

matolysis. The remarkable cassiterite pipes of the Potgietersrust tinfields illustrate this type. They evidently date from a period when the state of consolidation of the granite did not permit the formation of fissures in it. The writer has suggested elsewhere[1] that the pipes have developed from trains of tubular and lenticular miarolitic zones in the Bushveld Granite comparable with the trains of bubbles observed in glass melts.

4. Pipes formed by replacement along fissure or joint intersections in igneous or sedimentary rocks. Examples are certain cassiterite occurrences on the Potgietersrust and Rooiberg tinfields.

5. Pipes formed in dolomite by ascending magmatic waters. In this category falls the Witkop Zinc Pipe, situated near Otto's Hoop, in the Western Transvaal. It is analogous to the Duluth and Pilares pipes, as described by Locke,[2] who attributes the origin of these deposits to *mineralization stoping,* which, in his own words, is "the removal of rock along trunk channels by rising solutions during an early stage of their activity; collapse and brecciation of the rock thus left unsupported, and the deposition of ore and gangue minerals in the brecciated mass."

There are probably other types with which I am not acquainted; but enough has been said to show that mineral pipes are of great interest and importance alike from the scientific and economic points of view, and that they merit far more notice than they have received hitherto.

PERCY A. WAGNER.

[1] ECON. GEOL., vol. 21, p. 728, 1926.
[2] ECON. GEOL., vol. 21, pp. 431–453, 1926.

DISCUSSION AND INFORMAL COMMUNICATIONS

NOTE ON THE ORIGIN OF THE RIO TINTO ORE BODIES.

Sir: After a year's intensive study of the surface and underground conditions at the Rio Tinto Mines in the Province of Huelva, Spain, I have been led to a theory as to the origin of the great ore bodies in this region. As this theory or working hypothesis has already borne fruit inasmuch as it has led directly to the finding of several new ore masses, it is deemed worthy of brief mention here in advance of the full discussion which will appear later.

In the vicinity of the mines there are two masses of quartz porphyry. The southern mass is a sill which has been injected along the cleavage of the slate. To the north of this sill and separated by slate there is another porphyry intrusion which appears to be a dike. On its southern flank it either undercuts or reverses the dip of the slates. On its northern flank it has a conformable intrusive contact with slates, *i.e.*, the strike and dip of the porphyry-slate contact are the same as the strike and dip of the slaty cleavage. Within the porphyry area there are numerous isolated bands of slate. The North Lode group is entirely surrounded by porphyry. On the other hand San Dionisio, Eduardo and South Lode are on the south contact between porphyry and slate. Planes is at the eastern nose of the dike with mineral between its slate roof and the porphyry.

The porphyry, which is near a mineral mass, is fractured and also sheared. The shearing appears as an approximation to a rough irregular cleavage. The fracturing gives a coarse cross pattern and the fractures are now filled with pyrite, chalcopyrite,

and gangue. The ensemble of these veinlets is called a stockwork.

The stockwork is always found below or to the side of the massive ore minerals and extends both horizontally and vertically for considerable observable distances from the masses.

I believe that the masses were fed from depth by the solutions traversing these channelways.

In regard to the shearing and fracturing it would appear that forces other than those usually termed orogenic, *i.e.*, large scale tangential compressive forces, must be called in to explain their origin. The reason is that any forces of sufficient magnitude to shear and fracture the porphyry would have pulverized the slates to a degree not seen in the areas around the dike. It follows that one should look for the cause within the porphyry mass itself. Where the stockwork is strongest there is less shearing and vice versa. Furthermore, the strike and dip of the shearing approximately parallels the contact of the porphyry and slate. These facts seem to indicate (*a*) that the shearing is the result of injectional pressure, and (*b*) that the shattering took place following the crystallization of the magma when torsional forces were brought into play by slight upward or downward movements of the semi-liquid magma beneath its chilled roof. Where a shear structure existed, the movement was taken up along the already existing lines of weakness, but where the magma had crystallized normally the result was a shattering. The pattern of the shattering on any plane resembles closely that which was produced by Daubree [1] in his classical experiment on the torsional effects on a glass plate.

As the magma cooled, pressures were brought to bear on the interior of the porphyry mass and the mineral bearing solutions were caused to circulate upwards through the fractured zone. These solutions replaced the softened and cominuted slate, which had suffered alteration by the intrusion of the porphyry, and to a certain extent the porphyry itself. It may be asked why all the slate at the slate-porphyry contact is not thus altered and there-

[1] "Etudes synthetiques de Geologie Experimentale." Paris, 1879.

fore in a state favorable for replacement. The answer is that where the porphyry has cut across the slaty cleavage or where the porphyry has included keel-shaped masses of slate, it has had the opportunity of altering the slates. Where the porphyry has simply slid up along the slaty cleavage there has been little alteration because the slate is almost impermeable to solutions in a direction normal to a cleavage plane.

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CHANGES IN THE OXIDATION OF IRON IN MAGNETITE.

TWO KINDS OF MAGNETITE?

Sir: Due to my absence abroad, I did not see Miss Twenhofel's paper with the title, "Changes in the Oxidation of Iron in Magnetite"[1] until very recently and Mr. Gilbert, who discussed parts of this paper anticipated some of my remarks.

Miss Twenhofel thinks that I seem "to question whether such oxidized material actually has the magnetite structure" and that I take no account of this oxidized magnetite's "being a proper oxidation product of magnetite and formed intermediately in the change from magnetite to hematite." A careful examination of the footnotes (p. 390) of my paper[2] will show that the chief paper by Welo and Baudisch in the *Philosophical Review* had not yet come to my attention when I wrote my paper, and the one by Sosman and Posnjak on "Ferromagnetic Ferric Oxide Artificial and Natural" I found just before I received the proof. Since my paper was based chiefly on microscopic examination of polished sections, I could not have detected any "oxidated magnetite" if it is identical in appearance to true magnetite, as Miss Twenhofel seems to believe. She, as well as the other investigators, report brown and reddish-brown powders of oxidized

[1] ECON. GEOL., vol. 22, pp. 180–188, 1927.

[2] "Magnetite-Martite-Hematite," ECON. GEOL., vol. 21, pp. 375–393, 1926.

magnetite. If the colors of the powders of the oxidized and unoxidized magnetite are different one would expect a noticeable difference in the colors when seen in reflected light. This seems to be borne out by some observations of W. H. Newhouse and W. H. Callahan, whose recent paper, "Two Kinds of Magnetite?"[3] is very important. Unfortunately no photomicrographs accompanied it and therefore it is difficult to get an idea of how slight the color difference in polished sections of their brown and blue magnetites are. They write, however, that "unless both minerals are in the field it is hard to determine which one is present." Personally I have not observed brown magnetite that would answer their description. In the Mesabi martite ores it must be practically absent, for large samples of crushed wash ore examined by the mining companies and by me[4] contain no magnetic material, with the exception of a trace of bluish-black magnetite.

The appearance in my experiments of the lath-shaped hematite crystals along the octahedral planes in the specimens upon heating (but not above 200°) Miss Twenhofel tries to explain quite differently. According to her hypothesis, oxygen atoms enter at random in an irregular fashion (avoiding concentration along any one plane) into the magnetite, producing "oxidized magnetite." "Then if such irregular movement were carried far enough (*i.e.*, over a long enough period of time or hastened by a higher temperature) some of the oxygen atoms might find those positions of weakness on the octahedral planes and there break down the structure and form hematite, whereas the other parts of the mineral would still retain the magnetite crystal structure and consist of wholly oxidized magnetite, partially oxidized magnetite, and unchanged magnetite." Now if the oxygen atoms are at liberty to occupy any vacant space in the crystal lattice and if they do so, why should hematite begin to form along the octahedral planes of weakness? It would seem to me that such hematite would act as seed crystals do in oversaturated solutions. At fairly high tem-

[3] ECON. GEOL., vol. 22, p. 629, 1927.

[4] "Contributions to the Geology of the Mesabi Range," Minn. Geol. Surv. Bull. 19, p. 43, 1924.

perature and under oxidizing conditions it would appear that the "oxidized magnetite" (which surely is a relatively unstable product under those conditions) should change rapidly to hematite, as hematite is already present in many places. In geological processes then, where temperatures change very slowly, it does not seem probable that much of the material could be left at this intermediate stage of "oxidized magnetite."

Of course it is also possible that the lath-shaped particles of hematite which I obtained in my experiments were really "oxidized magnetite"—that is, had the composition Fe_2O_3 but still the structure of magnetite, but to prove this is hardly possible at present, for the quantities of this artificial material are extremely small and cannot be separated from the magnetite in which they are enclosed. This possibility, however, that the lath-shaped particles are "oxidized magnetite," if an intermediate product is present at all, seems more reasonable, as there is the afore-mentioned difference in the colors of the powders of the compounds.

Miss Twenhofel's "theoretical considerations as to positions of extra oxygen atoms in oxidized magnetite" need discussion. According to her, the placing of the extra oxygen atoms in those positions which Welo and Baudisch selected, would add 32 "to a plane which already has an atomic weight of 111.7, making a 29 per cent. increase in weight. Inasmuch as the intensity of a given line of the X-ray pattern is a function of the weight of the atoms comprising the plane from which the X-ray is reflected to make that particular line, it would seem that this large increase in the weight of the atoms on the 1 0 0 plane should visibly affect the line formed by the ray reflected from that plane and it should appear much more intense in the oxidized magnetite pattern than in that of magnetite. That no such difference is visible throws doubt on Welo and Baudisch's conclusion as to the positions of the extra oxygen atom." This reasoning at first sight seems correct, and it would be if these planes with the extra oxygen atoms had not interleaved with them other densely populated planes to which nothing is added (addition in the algebraic sense). As it is, conditions are much more complicated because

the reflections from the interleaved planes are out of phase with the others, and therefore, give interference just as in other wave motions. The resultant wave amplitude can be computed by adding vectorially the impulses from all atoms in a unit cell. Care must be taken not to count in too many atoms. For example, the eight atoms in the corners of the cube count only as one.[5] The intensities of reflections are proportional to the square of the amplitudes. Or

$$\text{Intensity approximates } (A^2 + B^2)$$

$$A = \sigma_1 \cos 2\pi n(hx_1 + ky_1 + lz_1) + \sigma_2(\cos 2\pi n(hx_2 + ky_2 + lz_2) \cdots + \sigma_s \cos 2\pi n(hx_s\ ky_s\ lz_s)$$

$B = \sigma_1 \sin 2\pi n(hx_1 + ky_1 + lz_1) + \cdots$ continued for the sine members as for cosine members above. σ is the scattering power of each atom (respectively ion), n is the order of reflection, $h\ k\ l$ are the indices of the reflecting plane, $x\ y\ z$ are the coördinates of each atom. The subscripts 1, 2, 3, . . . s have reference to the various positions in the unit cell. In magnetite we have 56 ions in the unit. Our subscripts, therefore, would run up to 56.

For reasons which cannot be given in this short discussion there exist I., II., III., IV., etc., order reflections. The intensities decrease very rapidly in approximately this proportion:

Orders	I	:	II	:	III	:	IV	:	V
Intensities	100	:	20	:	7	:	3	:	I

Miss Twenhofel used the atomic weight for computing increases in atomic population of planes. It would be better to use the atomic numbers, and in a compound like magnetite it is customary to take the number of electrons of the ionized atoms. For example, the atomic weight of iron is 55.84, the atomic number of the neutral atom is 26, that of the ferric ion is 23, and of the ferrous ion 24.[6]

Applying the above considerations to magnetite and "oxidized magnetite" in the (1 0 0) plane, we find that the I. and III.

[5] For more information see Wyckoff, Ralph W. G., "The Structure of Crystals," New York, 1924.

[6] See references in my paper, ECON. GEOL., vol 21, p. 382, 1926.

order reflections are missing entirely in both compounds. The II. order is absent in magnetite, but *theoretically* a *faint* reflection should be noticeable in "oxidized magnetite." In the IV, order reflections there is a decrease in intensity due to the extra oxygen atoms, instead of an increase, as she supposes. The theoretical ratio of intensities would be approximately:

$$\frac{\text{magnetite}}{\text{oxidized magnetite}} = \frac{100}{84.5}$$

That would be a decrease of about 15.5 per cent. Such a small difference, especially since it occurs in two separate photographic records, probably could not be seen at all. Comparisons of intensities as recorded in diffraction patterns on film or plate, are very crude yet, due to the nature of the problem. For similar reasons the very faint II. order reflection in "oxidized magnetite," due to the extra oxygen atoms probably would escape detection, for its theoretical intensity as compared to the IV. order reflection is about 1 : 30.

For planes other than the (1 0 0) planes, conditions would be just as complicated. An attack of the problem by the X-ray powder method is of little promise, then, at present. Miss Twenhofel, in speaking of the structure model of magnetite, says, "and any number of positions have been found in which there is plenty of room for the small oxygen atoms." Recent investigations [7] seem to show that the oxygen ions are large compared to those of iron, for example, oxygen having a radius of about 1.30–1.35 Å and Fe^{II} 0.72–0.75 Å. If these radii are correct, there is no room at all for four additional O ions in the lattice. As a matter of fact, there is very little room even with radii thought correct only a short time ago.[8] This was one of the reasons why I placed the O ions in my diagram [9] each half way between two ferrous ions. We also have to consider symmetry in

[7] For literature see: Pauling, Linns, Sizes of Ions and Structure of Ionic Crystals. *Jour. Am. Chem. Soc.*, vol. 49, pp. 765–92, 1927.

[8] Bragg, W. H. and Bragg, W. L., "X-rays and Crystal Structure." London, 1925.

[9] *Op. cit.*, p. 381.

placing the four ions. Welo and Baudisch did that, but their O ions are placed in the centers of tetrahedra of Oxygen ions on one hand and *ferric* ions on the other and therefore, as well as on account of size, these positions look improbable. For this reason I placed the extra oxygen ions at the expense of symmetry. The distortion resulting by this placement would make the "oxidized magnetite" unstable except under very special conditions and for short periods of time, such as obtained in the laboratory. That was the way I explained the fact that martite, as far as we know, has the crystal structure of specular hematite. Of course, there remains the possibility of irregular distribution of the extra ions, as Miss Twenhofel describes, if it were not for their size. It is even conceivable that these extra ions could wander about in the structure, as has been suggested in the case of other compounds, or that they are not yet ionized, but neutral atoms of O, in which state they would have a much smaller diameter and could "slip through" in many places. Their ionization, then, would bring about a rearrangement of the structure to hematite.

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REVIEWS

Physico-Chemical Geology. By R. H. RASTALL. 248 pp., 62 figs. Longmans Green & Co., 1927. Price $6.00.

The author states in the preface that this book is an attempt to give, in connected form, an account of the application of some of the modern theories of physical chemistry to geological problems. The first chapter treats of the states of matter and the principle of equilibrium. However, several inconsistencies exist; for example, the author fails to make clear, in discussing the principle of LeChatelier, that it applies strictly only to reversible reactions and in Fig. 1 the lettering of the diagram must be changed to correspond to the text. Also, in the treatment of the phase rule, which is brief, it is stated that when $CaCO_3$ is dissociated, if any CaO or CO_2 be removed, it is necessary to choose new components, such as $CaCO_3$ and either CaO or CO_2; but this is obviously unnecessary and undesirable since Findlay's definition of components is used.

The second chapter of 36 pages deals with fusion and solidification; a number of binary systems (though Roozeboom's type IV. is omitted) are considered and three cases in a ternary system are reviewed briefly. The chapter closes with a treatment of double salts. In the reviewer's opinion, the first two chapters would be more understandable if the author had pointed out what part of the diagrams referred to pressure, and if he had shown that the freezing point is that point at which the vapor pressures of the solid and liquid phase are equal.

The third chapter treats of isomorphism and solid solution. A "molecular formula" of a mineral is used as an example, but it is expressed in weight per cent. rather than in mols, and in the text this departure from chemical usage is not pointed out. The chapter on polymorphism begins with a discussion of enantiotropy and monotropy and then turns to inversion in a binary system and incongruent melting. The author considers the dimorphous forms, pyrite and marcasite, also aragonite and calcite and says that no explanation of their relationship is known. Evidently he is unaware that the aragonite-calcite relation has been determined.

Chapter V. deals with the igneous rocks. The average composition of the crust, some aspects of petrographical provinces, the origin of porphyritic texture, and some of the effects of mineralizers are discussed in about 15 pages. The summary of differentiation and differentiation

processes is clear and, to the reviewer, seems to be the best part of the book; however, when the author includes under differentiation the zoning of mineral veins, the term seems to be overworked.

Chapter VI. pertains to mineral formation in igneous rocks and is largely a summary of the type of work done by the Geophysical Laboratory of Washington, from which most of the examples are taken. It should be noted, in passing, that in the system orthoclase, leucite, and silica, the liquid field is wrongly marked orthoclase and liquid.

The chapter on metamorphism treats of the thermal metamorphism of siliceous and argillaceous rocks, largely following Goldschmidt. In discussing the metamorphism of the calcareous rocks the author refers to the formation of wollastonite and its high temperature modification, and then states that fluxes must have been present to account for the formation of the mineral by lowering the fusion point below the inversion point. One wonders why fluxes and fusion point must be introduced to account for a metamorphic mineral in the temperature range in which it is stable. A few lines later the formula Ca_2SiO_4 is erroneously ascribed to monticellite. The remainder of the chapter is devoted to the metamorphism of dolomite and to dynamic metamorphism and metasomatism. The concept of depth zones in dynamic metamorphism and of volume relationships in metasomatism are not mentioned

In the chapter on weathering the alteration of certain minerals and rocks is discussed. But under the potassic feldspars there is no mention of the fact that microcline is commonly more resistant to weathering than orthoclase. The chapter on salt deposits is mainly a brief review of the work of Van't Hoff. In the latter part of the chapter some of the older views on the origin of dolomite are summarized.

A chapter of fourteen pages is devoted to ore deposits. The treatment is largely descriptive with little physical chemistry. The author points out the zonal arrangement of ore deposits about intrusives and then gives the usual classification on the basis of depth. Under secondary changes a few of the common equations for the oxidation of sulphides are given. According to him, chalcopyrite and bornite are commonly found as a result of secondary enrichment, a conclusion to which few economic geologists will subscribe. He places tetrahedrite, tennantite, and ruby silver among the secondary minerals and does not mention that in some of their occurrences they are primary. In fact, most investigators believe that tetrahedrite and tennantite are always primary. The chapter closes by a consideration of the bedded iron ores but much of the modern literature is not mentioned. From the point of view of physical chemistry this chapter is disappointing; there is no mention of the polymorphic forms of Cu_2S and ZnS, or of the chemistry of the precipitation of magnetite.

Chapter XI. on refractories and abrasives might well have been omitted; the discussion of the forms of SiO_2 and the composition of clays, which form the larger part of it, could have been placed in other chapters. The last chapter is on colloids in geology and is largely taken up with a discussion of hydrosols and hydrogels. The treatment is rather elementary and does not take into account some of the more recently published material. No mention is made of protective colloids or the action of electrolytes in rendering certain insoluble substances colloidal.

For the most part, the book is clearly written and it contains subject matter that should stimulate geologists. But, to the reviewer, it is disappointing not only because there is insufficient discrimination in choosing material from the older literature, but also because much of the more recent work is not mentioned. For example, the citations from the "Grundlagen der physikalisch-chemischen Petrographie" by Boeke are from the 1915 rather than the 1923 edition. Typographical errors are few, but errors in subject matter are more numerous. The publishers have produced a nicely printed and bound book but the price does seem high.

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Lehrbuch der Geophysik (Textbook of Geophysics). By B. GUTENBERG. Gebrüder Borntraeger, Berlin.

This book deserves, because of its completeness, rather the title of a "Manual on Geophysics" than that of a textbook. It presents an exhaustive description of all subdivisions of Geophysics. Such a manual has not been published in Germany for some time. The books published there recently deal with Geophysics from different viewpoints. The textbook written by Prey, Mainka and Tams presents more the theoretical side of Geophysics and does not, aside from this, deal with earth-magnetism at all. The book published by R. Ambronn aims only to give an exhaustive description of the methods of applied Geophysics. The textbook of Gutenberg is devoted mainly to pure Geophysics; one part of it, however, deals also with geophysical methods of prospecting.

The book will be published in 5 parts, of which at present, only 3 are issued (608 pages); the two others, when they appear, will be reviewed in these columns.

The three parts are subdivided in the following chapters:

1. *The evolution of the earth and its geological composition* (by A. Born). This part deals briefly with cosmogonical hypotheses, the material of the earth's crust and of the meteorites, geochemistry, radio-

activity, relative and absolute geological chronology, geographical classification of the earth's crust, and theories of evolution of continents.

In the opinion of the reviewer, it would have been advisable to include in this chapter, according to its title, an account of the methods of Paleography and the paleogeographic evolution of the earth.

2. *Gravity and Isostasy* (by E. A. Ansel). This contains Clairaut's Theorem, isostatic hypotheses of Pratt and Airy, normal gravity and its disturbances, computation of the isostatic reduction. Methods of measuring gravity by means of the pendulum and torsion balance are described in the chapter "Geophysical Methods of prospecting."

It would, perhaps, have been advisable to include in this chapter a mention of plumb-line deviations and a brief resume of Hecker's and Venig-Meinesz's determinations of gravity at sea. The determinations of the gravitational constant, and the Jolly balance are briefly dealt with in Chapter XI.

3. *The mechanism of movements in the earth's crust* (by A. Born). This deals mainly with epeirogenic and orogenic movements. A description of the movements of the crust due to seismic and volcanic action should, according to the title, be expected in this chapter also, but is given in chapters five and six.

4. *The three main geological factors; water, ice, wind* (by A. Born).

5. *Volcanism* (by A. Born). The different magmas, types and distribution of volcanoes, and the cause of volcanism.

6. *Geological Seismology* (by A. Sieberg), or, in other words, "Macroseismics." Classification of earthquakes, their intensity and frequency, relationship of earthquake-intensity to geological surface-conditions, effect and origin of earthquakes.

7. *Physical Seismology* (by B. Gutenberg). This chapter deals with the various types of seismographs and their theory, seismograms and the theory of propagation of seismic waves through the interior of the earth, the determination of earthquake data from the seismograms, the periodicity of earthquakes. The seismographs used for the investigation of artificial vibrations or explosions are described in the chapter on Geophysical Methods of Prospecting.

8. *Water waves and tides* (by B. Gutenberg). Types and theory of waves, theory of the water—and bodily tides.

9. *Movements of the axis of rotation of the earth* (by B. Gutenberg). Precession, nutation, variation of latitude, migration of the pole.

10. *Earth-Magnetism, Earth-Currents, Polar-Lights* (by J. Bartels). Magnetic Instruments and Methods, theory of the permanent earth-magnetic field and its constituents, local anomalies, the periodical and unperiodical variations, especially in relation to polar lights and earth-currents. Since in the chapter "Geophysical Methods of Prospecting" the local anomalies are also dealt with in detail, it would perhaps have been

advisable, for the benefit of the reader, not to separate this subject in two parts.

11. *The physical constitution of the earth* (by B. Gutenberg). Shape of the earth; density, pressure, rigidity, temperature, chemical composition and state of matter in the interior of the earth.

12. *Geophysical Methods of Prospecting.* This chapter will doubtless be the most interesting one to the readers of this *Journal.* It is again subdivided in various parts.

(*a*) *Gravity measurements* (by E. A. Ansel). Pendulum measurements, their theory and practice, theory of the torsion balance and of the corrections to be applied, effect of subterranean unconformities.

(*b*) *Earth-Magnetic Measurements* (by J. Bartels). General description of magnetic instruments, methods and corrections, effect of magnetic bodies, relationship of earth-magnetic to gravity-anomalies, examples. Considering the great variety of earth-magnetic instruments employed at present in prospecting, it seems to the reviewer that their theory could have been dealt with somewhat more in detail, inasmuch this has been done so thoroughly by the author of the previous chapter on gravity methods.

(*c*) *Electrical Measurements* (by J. Bartels). Artificial D. C. methods, especially those of Schlumberger, Wenner, Gish. Natural Currents; artificial A. C. methods (equipotential lines, intensity and direction of the magnetic field as produced by the electrical field), electrical waves.

This chapter could perhaps have been made more exhaustive, considering the great amount of work which has been done and published in Sweden, particularly in regard to the theoretical effect of deep mineral deposits on the D. C. and galvanic and inductive A. C. methods.

(*d*) *Artificial Elastic Waves as Applied in Prospecting* (by B. Gutenberg). Acoustic method of Fessenden, acoustic deep sea sounding, seismographs for measuring artificial vibrations and explosions, theory of the effect of subterranean unconformities, data on artificial seismic waves (to be continued).

C. A. HEILAND.

COLORADO SCHOOL OF MINES,
GOLDEN, COLO.

What Duty to Support the Surface Does a Subsurface Owner Owe? By ROBERT G. BOSWORTH. 10 pp. Technical Paper No. 1640–A–F (Advance printing subject to revision) A. I. M. M. E., New York, January, 1927. Published with Mining and Metallurgy.

The timeliness of this article and its importance to the coal mining industry recommends it to the attention of Mining Engineers and Geologists. A revival of interest in deposits of lignite coal, due in part to experiments of certain railroads in the use of lignite as a fuel for locomotives, is taking place in Texas. Lignite operators are affected to a greater extent even than are operators of bituminous coal mines by the decisions of the courts in regard to this question. This is because of the high percentage of lignite coal, 40 per cent. to 60 per cent., which it is necessary to leave in the mine to support the surface of the ground.

The author accuses courts, judges and lawyers in this country and England of much loose thinking on this subject and of a blind following of precedent without proper weighing of circumstances and without proper distinctions of fact. If the author's conclusions are correct—and they seem eminently just—much injustice has been done for a long time to coal operators in litigation on this question.

By drawing clear distinctions between a *reservation* and a *grant*, the author shows that there are two types of cases involving the severance of the surface and subsurface estates when no specific definition by contract of the duty of the operator in regard to the support of the surface has been made.

Type 1. The owner, A, of both the surface and subsurface, grants by deed or lease to B, "all coal with full right to work and win the same," reserving for himself, A, the surface. This is a grant of coal.

Type 2. The owner, A, of both the surface and subsurface, grants to B, the surface of the land, reserving to himself, A, "all coal with full right to work and win the same." This is a reservation of coal.

In each case a third person can acquire from A only such rights as A had and no more.

The principle of law upon which the author makes his decision with regard to the duty to support the surface is that a grantor may not later derogate (partially annul) his grant. The conclusion drawn is that those who hold a *grant* of all coal are entitled to it regardless of surface rights. Those, however, who hold a *reservation* of coal are bound to preserve the surface which they or their predecessors in title have granted.

A summary of the present apparent state of law, as established by prominent rulings of the courts, is given. The courts seem to have de-

cided that, "the right to surface support in the absence of express or implied waiver is an absolute right." The author points out that in all the cases cited the absolute rule enunciated by the court is then qualified as in the quotation just given, but that all the courts seem to have held, up to the more recent decisions, that a grant or reservation of, "all coal with full right to work and win the same," was never sufficient to constitute either an express or implied waiver of the right of surface support. The author maintains that there is no logical basis for such a rule.

There is but one case, within the author's knowledge, where a court has held according to his conclusions set forth above. That case has not as yet reached the court of last resort, and, therefore, cannot yet be cited as a precedent. It is generally many years after the grant or reservation is made that a dispute arises as to damages to the surface and the contracting parties are frequently unable to foresee many of the results that may arise from the mining of coal under changing surface conditions, such as: Later exploitation of surface deposits of gravel, etc.; or weakening of the subsurface and surface strata caused by seepage accompanying irrigation. The author discusses a number of interesting special cases and their bearing on the question of the operator's relation to surface conditions.

An important conclusion following from the discussion of this question is that all instruments conveying title to coal or to coal lands should clearly define the rights of both parties as to the maintenance of existing surface conditions. An owner of the entire fee to coal lands would, if he were to convey the surface rights to another, by deed or lease, greatly reduce the value of the mineral rights reserved (in the case of coal or lignite) unless he took pains to free himself, in the instrument of conveyance, of all obligation to support the surface.

This question is far less important in the underground mining of metallic ores because the nature of veins and lodes is such that subsidence is not a common occurrence.

W. ARMSTRONG PRICE.

HOUSTON, TEXAS.

Soil Mineralogy. By F. A. BURT. Pages 82, figs. 6. D. Van Nostrand Co., N. Y., 1927. Price $1.50.

Soil Mineralogy is intended by the author to furnish agricultural students with a description of the most important soil-making minerals and the alterations effected in them by weathering agents.

It gives a very brief discussion of the characters by which the individual minerals are recognized; contains a short discussion of weathering; describes about 65 minerals and groups of minerals and devotes five pages

to directions for determining them. In short the volume is an elementary text that deals with a limited number of mineral species. The only difference between it and any other elementary mineralogy is the emphasis which it places on the relation between the minerals discussed and the soil.

It seems rather unfortunate that the determination of the minerals is made to depend solely upon their chemical features. It is probable that the methods employed by the author will distinguish between the few minerals discussed by him but they will not differentiate between those which he has discussed and others which are apt to be met with in river deposits and glacial soils. For instance, kaolinite is distinguished by the fact that its hardness is less than three; it is not micaceous and is not affected by hydrochloric acid; does not fuse to a magnetic mass and shows no magnesium reaction.

W. S. B.

Grundlagen der Petrographie. By O. H. ERDMANNSDÖRFER. Pp. xii + 327. Ill., 119. Ferdinand Enke, Stuttgart. 1924.

This little book deals with the physico-chemical principles underlying the formation of igneous and metamorphic rocks. It treats of the progress of the magma from its source to its end in the solid rock, and consequently, discusses many of the processes concerned in the making of ore-veins. The portion treating of metamorphism describes the reactions concerned in the production of contact minerals and those produced by dynamic and metasomatic agencies. The chapter on pneumatolitic metasomatism is particularly applicable to the alterations effected in country rocks adjacent to veins. The development of the subject is simpler than is usually the case in texts covering a similar field.

W. S. B.

What the Coal Commission Found. Edited by EDWARD EYRE HUNT. Assistant Secretary of Commerce, with contributions by sixteen authors. 416 pp. Williams & Wilkins Co., Baltimore, 1922. Price, $5.00.

This book presents in simple form the substance of the 3,000-page report of the U. S. Coal Commission appointed by President Harding in 1923 under the chairmanship of John Hays Hammond. It is a summary volume prepared by certain members of the Commission staff for the use of the public. It deals briefly with many of the problems presented in the original reports. It is well written, edited, and printed, and is a handy volume to which to turn for information relating to the coal industry.

SCIENTIFIC NOTES AND NEWS

N. H. Darton, of the U. S. Geological Survey, has returned after six months spent in exploring the geology of the eastern slopes of the Andes in Venezuela.

F. L. Ransome, of the California Institute of Technology, has been making a geologic study of the United Verde Extension Mine at Jerome, Arizona, and will return to Pasadena in December.

Charles W. Wright, who has been operating mines in Sardinia and northern Italy for the last eighteen years, came to the United States in September to take up permanent residence at 2128 Wyoming Avenue, Washington, D. C.

Sydney H. Ball has returned to New York after a professional trip to Mexico.

M. N. Short, of the Geologic Branch of the U. S. Geological Survey, is to lecture at Harvard University this season, giving part of his time to work for the Survey.

W. G. Woolnough, professor of geology at the University of Sydney, has been appointed for a term of six months as geological adviser to the Australian Commonwealth Government.

E. Gail Carpenter, formerly with the Sinclair Oil and Gas Company, at Enid, Okla., has taken a position with the Foster-Reiter Company at Tulsa.

Sidney Paige has been appointed administrative geologist for the Amerada Petroleum Corporation at Fort Worth, Texas.

E. C. Andrews, Government geologist of New South Wales, has returned to Yale University to prepare for publication his Silliman lectures delivered last spring.

Waldemar Lindgren is at Washington, D. C., as chairman of the National Research Council.

L. C. Graton is now in South America.

Charles White, whose geological work on croppings at Cananea resulted in the recent ore discoveries there, has gone to Australia on professional business.

E. L. DeGolyer has returned to his office in New York City.

Edwin Bimmey, Jr., is at present in Cody, Wyoming.

John W. Gruner has returned to the University of Minnesota after some months of study abroad.

H. D. Smith, of the United Verde Copper Company, has gone to London, and expects to return to this country about December 1st.

P. S. Smith, of the U. S. Geological Survey, has returned to Washington from Alaska.

Ralph Ilsley, formerly with the Sun Oil Company, has taken a position with the Roxana Petroleum Corporation at Dallas, Texas, as micropaleontologist.

Quentin D. Singewald has left the Compania Transcontinental de Petroleo of Mexico to become assistant professor of geology at the Colorado School of Mines, Golden, Colo.

Lester C. Uren, professor of petroleum engineering at the University of California, is now director of research work of the Ranney Oil Mining Company.

E. Kaiser, professor of geology at Munich University, lectured in August at Johannesburg, under the auspices of the Geological Society of South Africa, on Surface Geology in Arid Climates.

H. T. Hamilton, of San Francisco, has taken a position with J. F. McClelland, in the Industrial Department of the New York Trust Company.

Frank Reeves, of the U. S. Geological Survey, is taking a four months furlough, and is engaged in exploratory work in western Canada.

Arthur Watts Allen has been appointed editor of the Engineering and Mining Journal. He brings to this position a wide experience in the mining fields of the world and demonstrated journalistic capabilities.

Herman Gunter has been reappointed State Geologist of Tennessee.

C. L. Tanton, of the Canadian Geological Survey, has been investigating the recent discovery of placer gold at Fort William, Ontario.

Louis D. Huntoon returned to New York in October after investigations in the Sudbury area, and is now engaged in further examinations of properties in Quebec and Ontario.

J. J. Beeson, of Salt Lake City, recently sailed from New York to Puerto Colombia, to examine a tin property near Bogota.

E. K. Soper, consulting geologist of Los Angeles, California, has been appointed associate professor of geology at the University of California.

William L. Russell has returned to New Haven, Conn., from Venezuela.

The U. S. Geological Survey has issued a revised oil and gas map of Texas.

Dr. Eugene Allen Smith, for fifty-four years the State Geologist of Alabama, died recently at the age of eighty-six.

The New England Intercollegiate Geological Excursion was held October 14 and 15 in the vicinity of Worcester and Clinton, Mass. The Worcester "coal mine," glacial features, and older rocks were examined.

The Fifteenth International Geologic Congress will be held in South

Africa, July 29 to August 12, 1929. The officers are: Honorary President, The Premier of the Union of South Africa; President, A. W. Rogers; General Secretary, A. L. Hall; Assistant Secretaries, L. T. Nel, F. C. Partridge; Treasurer, E. H. Banks.

Provisional subjects for special discussion are: Magmatic Differentiation; Early Glacial Periods; The Karroo System; and the Gold Resources of the World.

The excursions have been chosen with great care, and avoid conflicting interests. The pre-Congress ones are: (1) Economic Geology, Kimberley and the Rand (several days); (2) General, Cape Colony—folded mountains, stratigraphy, Dwyka glaciation, and Kimberley diamond mines (long); and (3) short excursions to (*a*) Table Mountain, (*b*) Chapman's Peak, (*c*) Contact metamorphism at Sea Point, near Cape Town. Short excursions during the Congress are: (4) Premier Diamond Mine; (5) Salt Pan, a saline caldera lake; (6) Bushveld Igneous Complex; (7) Johannesburg gold mines and glacial deposits (three days); (8) Rustenburg platinum deposits. Post-Congress excursions are: (9) Choice of (*a*) Vredefort granite dome (three days); (*b*) Devil's Kantoor, the eastern Escarpment and asbestos deposits (two days); (*c*) Stormberg—stratigraphic, Karroo and Port Elizabeth; (10) Long excursion to the Bushveld Complex, including tin and platinum deposits; (11) to Southern Rhodesia(?).

The Committee are to be congratulated on cleverly arranging some short excursions to the same places as the longer ones; for example, the chooser of No. 2 misses the Rand of No. 1, but can see it by No. 7 later on; or if one does not choose the long Bushveld excursion of No. 10 he can still see some of it in No. 6.

The Committee are, wisely, giving greater importance to the excursions than to the papers, and the latter consequently may have to be somewhat limited.

Communications should be addressed to the General Secretary, Fifteenth International Geological Congress, P. O. Box 391, Pretoria.